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On Principles and Practices

The principle on which NUCLEONICS' editorial policy logically is based may be found nicely phrased in the Atomic Energy Act of 1946: " . . . the dissemination of scientific and technical information relating to atomic energy should be permitted and encouraged so as to provide that free exchange of ideas and criticisms which is essential to scientific progress."

The dissemination of scientific and technical information is itself important. Yet with the late Sir Arthur Eddington, we realize that knowledge is not the only thing that counts. We allow ourselves to speak of the spirit of science. It is this realization that prompts editorial comment on security and secrecy, two separate and fundamental issues of interest to scientist and layman alike.

There is a difference between secret matter and matter that is merely stamped SECRET. By itself the rubber stamp of SECRET classification is essentially administrative. Classification can no more establish or maintain a secret than can the acts of a legislative body change the ratio of a circle's circumference to its diameter from the transcendental number pi to $22/7$. Both acts have been tried; both inevitably failed.

As all scientists and engineers realize full well, the fundamental facts of nuclear fission have been known for a decade. Some of these facts have been front-page news since President Truman's announcement of the first atomic bomb burst. Moreover, even conservative scientists have stated the probable practical effects of nuclear fission, from its first announcement in 1939. Professor E. H. Kennard at Cornell University wrote in 1942, for example, "In this way a bit of uranium might perhaps be made to act as a tremendously strong explosive; or, if the process could be controlled, we should have an atomic source of power."

The facts of nuclear fission did fail to obtain much public notice in 1939, being printed on page seventeen of one New York newspaper for example. But even the most indifferent and scientifically uninformed of the literate public know of the atomic bomb now. They must be brought to realize that scientists everywhere have had the basic knowledge of fission available for ten years, and that in all reason there is little if anything concerned with these facts that can be claimed SECRET.

Much engineering and many techniques lie between knowledge of the fundamentals of nuclear fission and the complete mastery of atomic energy for war. This is the only possible proper domain of secrecy for military security in the science and engineering of atomic energy. But even here one must weigh the facts carefully to insure that the losses do not overbalance the gains of classification with its consequent inertia and clumsiness.

What is important and most urgently needed is the declassification of all classified matter that is not of military security significance and, of even greater importance, that new knowledge be left unclassified as a routine unless positive evidence is at hand that it must be classified for military security. These actions need not be expected to bring the millenium over night, but their doing would help clear the atmosphere of present fuzzy thinking and misunderstanding.

Security and secrecy are not all important, for the daily work must still be done. NUCLEONICS will continue actively to encourage publication of survey and review articles. Original contributions are also sought, not so much of discovery in the scientific sense of the term, as in what the great lecturer John Tyndall called the exercise of ingenuity. The facts of the expanding atomic energy industry will be covered in the form best suited to the needs of NUCLEONICS' readers.

The full impact of the atomic industry on man's daily living has yet to be felt. No one in his senses will assert that radiation and every other aspect of atomic energy will leave his business or profession unaffected. Labor laws, insurance policies, and public health have been or will be concerned. Agriculture, transportation, manufacture, and communication are affected. Irradiation of food is already used to tenderize beef, and future developments are certain to change the problems of feeding the world's billions.

To the layman in science, the most obvious single field of atomic energy in peace is industrial power from nuclear reactors. The importance of the field is obvious, and had atomic power been sought from 1939 to the present through "that free exchange of ideas and criticisms which is essential to scientific progress," there is no doubt civilization would be further advanced *in all countries* than it presently is. The fact is that "free exchange" was not permitted and encouraged, so that much remains to be discovered as well as disseminated, not only for industrial atomic power to become a reality but to permit evaluation of the impact of the entire atomic industry on all civilzation.

Unlike many technical journals and unlike journals of the learned societies, NUCLEONICS is free of commitments to any specialized professional group. NUCLEONICS is free to shape itself best to serve the atomic energy field generally and internationally.

Education for NUCLEAR ENGINEERING*

By KENNETH D. NICHOLS, Maj. Gen., USA
Chief, Armed Forces Special Weapons Project, National Military Establishment
Washington, D. C.

THE NORMAL engineering approach to the solution of problems is as applicable in the field of nuclear engineering as in any other branch of engineering. Some of the nuclear engineering problems encountered by the Manhattan District, a few of those presently encountered by the Atomic Energy Commission, and some of the steps that have been taken by universities to meet the need for engineers trained to handle these problems will illustrate this fact.

In the early days of the Manhattan Project, primary problems involved not only science but, even to a greater extent, engineering and industrial management. Research and development had to be completed, and organizations obtained (or built up) to design the necessary production plants, construct them, and then operate them for plutonium and uranium-235 production. In addition to research and development, a considerable amount of engineering was necessary if a practical bomb was to be developed. The scientists on the project at that time recognized the existence of typical engineering problems but few of them realized the complexity or the magnitude of the engineering that would have to be devoted to their solution before the project could be accomplished.

I was fortunate to be able to observe how many of the problems that confronted the Manhattan District were solved. To find engineering contractors to design the production plants was the first problem. Our selection was Stone & Webster. Although we realized that they could not handle all the problems, we needed a vehicle to make engineering studies on everything, so their original contract was made very broad and comprehensive. Shortly after the selection of Stone & Webster, it was obvious to us and to the physicists in Chicago that a great deal of chemical engineering had to be done if a chain reaction pile for production of plutonium was ever to prove itself practical.

The chemical problems associated with the plutonium project, for instance, were tremendously underestimated. As contracting officer, I sat down to do some estimating with the Chicago physicists, the microchemists who knew what was to be known about the chemistry of plutonium that had been de-

* This article is based on a speech delivered by General Nichols at the meeting of the Middle Atlantic Section, American Society for Engineering Education, held at the U. S. Military Academy, West Point, N. Y., May 14, 1949.

There is no mystery about atomic energy that good engineering cannot solve

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Kenneth D. Nichols, Maj. Gen., USA, B.S., C.E., M.C.E., Ph.D., who was District Engineer of the Manhattan District, is an able spokesman for nuclear engineering education. In acknowledgment of his expert approach to difficulties that early beset A-bomb planners working on U^{235} and plutonium research and production, the Smyth Report paid tribute to his "exceptional understanding of the technical problems and their relative importance." Holder of the Distinguished Service Medal and Order of the British Empire, General Nichols retains his chair at West Point as Professor of Mechanics while on active assignment in Washington as Chief of the Armed Forces Special Weapons Project, National Military Establishment. In addition, he is Deputy Director for Atomic Energy Matters, Plans and Operations Division, General Staff, U. S. Army, and a member of the Military Liaison Committee to the Atomic Energy Commission.

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rived from less-than-milligram lots, and with engineers from du Pont. How many dollars' worth of plant would be necessary to develop a practical semiworks for the chemical process? Three million dollars was the figure arrived at—although most of us thought it might be on the high side.

One month later du Pont had gotten into the problem enough to realize that neither two nor three million would touch the problem. Not only that, they felt the whole project needed a thorough engineering review to determine if the many engineering problems involved, not only in the plutonium project but in the U^{235} and weapon development projects as well, could be solved in a reasonable length of time. As a result, a committee consisting essentially of engineers was set up. It did its work between September and November, 1942. They made preliminary cost estimates that turned out to be reasonably accurate, and recommended the types of organizations that were necessary to design, construct and operate the plants involved in the Manhattan Project.

On the U^{235} end of the project the task involved engineering problems equally as difficult as those on the plutonium project. The basic scientific work on the physical separation of U^{235} and U^{238} was extraordinarily well in hand, but in this case too the research

NUCLEAR ENGINEERING

In tracing the history of nuclear engineering, we do not have to go back very far. It was as recent as the last 1890's that radioactivity was discovered and radium isolated.

In the 1930's various scientific accomplishments made possible a practical and military application of atomic energy: Chadwick, in England, discovered the neutron; Ernest Lawrence, in California, developed the cyclotron; Rutherford, Cockcroft, and Fermi and others made notable advances in the transmutation of elements and demonstrated Einstein's law concerning the mass-energy relationship.

In 1939, a startling discovery in Germany made practical the atomic bomb. The isotope U^{235} was found to be fissionable. Fortunately, Lise Meitner correctly interpreted the results of her experiment, and even more fortunately, she communicated with Niels Bohr in Denmark who in turn came to this country and discussed this startling discovery with Einstein and other scientists working here. We may be extremely grateful that the physical scientists not only recognized the scientific

on the supporting chemistry lagged behind. In the electromagnetic plant, for instance, there were those early days when no matter how much material was put into the production pipeline nothing seemed to come out and the project's leaders were joshed for attempting to produce vanishing quantities of U^{235}.

We were faced with the single chemical problem of separating U^{235} from associated gunk. Because of the small quantity of U^{235} and the extremely large quantities of gunk, consisting of a mixture of many other elements, here, too, normal chemical engineering did not apply. A precision of recovery was required that far exceeded normal production standards, but production engineers, assisted by research chemists and research engineers, finally devised and set up the necessary production line technique.

As a means of defining the need for engineers in the atomic energy field I could enumerate other examples and give more adequate recognition to the many industrial firms that formed a part of the team that put over the Manhattan Project. However, I prefer to draw on history only to the extent I have done to illustrate how the engineering approach for evaluating the task and organizing for the job was successfully applied.

The Present and the Future

Out of our experience on the Manhattan Project and in planning for the development of atomic power it has become clear that the future of atomic energy depends primarily on how well engineers do their job. Let us look at some of the specific problems involved in nuclear engineering. In a pile, whether it be for production of plutonium for bombs or for production of commercial power, the engineer is faced with new and difficult problems with which he has had little experience; and during the war he had practically none. At the present time many engineers have the experience derived during the war, but most engineers lack additional educational training that permits them to solve these new problems without learning new principles required by the atomic era.

and practical importance of the discovery but had the ability and persistence to sell it to their government. From 1939 until 1942 the bulk of the work in the United States was pure and applied research, although some thought was being given to the engineering problems of atomic bomb production.

In June of 1942, President Roosevelt favorably received the recommendation of Bush, Conant, and the other interested scientists, that atomic bombs were not only feasible but should be developed and produced as early as practicable. Shortly after, the Manhattan District was formed to carry out all aspects of design, construction, and operation of the necessary production plants.

With the successful detonation of the first atom bomb in New Mexico in July, 1945, the nuclear engineering accomplishments of the Manhattan District became readily apparent. With the same event, the engineering profession discovered they had a new branch. Nuclear engineering, a hot-house sproutling forced through early growth, already showed signs of becoming a sturdy and very permanent limb.

Shielding. Take, for example, shielding against radioactivity necessary wherever you have a chain reaction or radioactive materials. Here engineers were and are faced with strange requirements. One material might stop one type of radioactivity but not another. Moreover, some materials merely convert one type of radioactivity to another. Health physics is involved and there is little industrial background for making the necessary statistical studies.

Gadgeteering and remote control. One aspect of shielding is protection of the workmen. Another equally important aspect is the remote control and maintenance problem. In the chemical processes, or in the working of the pile itself, the process equipment must be controlled and maintained by remote control methods. Intensive gadgeteering was and is necessary for doing this type of work. At Hanford, complete chemical processes had to be capable not only of operation by remote control but also of maintenance by remote control. Some of the gadgetry involved is what we are now depending upon as a delaying factor in other nations' attempts to make atomic weapons.

Chemical recovery. Also involved in nuclear engineering is a need for precision of recovery not normally encountered even in the light chemical industry. The value of plutonium or U^{235} is so high that extremely high percentage of recovery is necessary in any ancillary chemical process in the production of power if such power is to be competitive with other sources of power. Not only is such precision chemical engineering complicated by the need for remote control apparatus, but also the transmutation from one element to another of the attendant products is a complicating factor. The control of radioactive wastes, both liquid and gaseous, must be done to a degree not generally recognized by other industries. Many millions have been spent at Hanford in the control of these liquid and gaseous wastes and, if commercial power is ever to be practicable, even greater effort must go into this problem in order to secure an economical solution. The chemical engineering involved in the production of

power or in the production of plutonium is the major problem that must be more efficiently solved if we are ever to have competitive atomic power.

Heat exchange. Here we have problems that are beyond the experience of most of the experts in this field. In the heat exchange problem, we are faced with taking a tremendous amount of heat out of a very small volume. The problem is further complicated by radioactivity. We must consider the nuclear properties of the coolants used for transmitting power from source to machine. We must consider both the effect of the coolant on the nuclear reaction and the effect of the reaction on the coolant. The temperatures involved are such that liquid metals may be the only suitable coolants. When we combine all these problems with the known characteristics of materials, we find ourselves working with some very nasty materials that introduce added problems of safe handling.

Materials and metallurgy. Throughout the pile we are confronted with engineering problems concerning materials and metallurgy. The materials used in the piles must meet functional and structural requirements and must stand up against the high temperatures involved. Not only must they stand up against temperatures with which we have insufficient practical experience, but they must also have the proper nuclear properties. Here again the materials may affect the nuclear reaction or the effects of the nuclear reaction on these materials may be such that the physical properties of the materials, such as the structural strength, conductivity, or molecular structure, are changed to such an extent that they no longer fulfill their basic missions. Here the research engineer must work with the physicists, for a tremendous amount of work must be done to determine the nuclear properties of ordinary structural materials and to develop new materials that can be produced in quantity and have the proper nuclear properties.

Economic problems and industrial safety. Dependable methods and equipment must be developed that are far beyond our normal industrial standards. It is costly to maintain equipment by remote control or abandon it when something goes wrong. If the economic problems of atomic power are to be solved, great dependability must be built into even the ordinary equipment—greater than is required for the equipment of any other industry.

Other engineering problems involved pertain to industrial safety. Unfortunately, many of the scientific personnel involved in the development of nuclear energy do not have practical experience in industrial safety. The result is that unusually high standards have been set. Industrial safety engineers will eventually have to solve this problem and get it on a practical scale if we are to have economical nuclear power plants.

Industrial uses for radioactivity. In solving all of these engineering problems

Sir John Cockcroft, director of the Atomic Energy Research Establishment [at Harwell, England], spoke of the closer integration which he expected to see between chemical engineers and the processes of nuclear energy. One thing he thought was quite clear to those who looked on the chemical engineer from the outside—that his position and importance in the world was increasing.

—From a report on a recent meeting of the Institution of Chemical Engineers. The Chemical Age. *April 30, 1949*

the solution must be based on the needs of the operator or producer. A theoretical solution is of little value if it cannot be applied on an industrial scale. The engineer, by training and tradition, is accustomed to meeting the needs of the industrial operator in like problems pertaining to other fields. He has bridged the gap between the scientists and the industrialists in such other engineering fields as electrical engineering, chemical engineering, metallurgical engineering, mechanical engineering, power and other, and there is no reason why he cannot render the same service in the field of nuclear engineering.

More engineering problems are attached to the application of radioactivity or the use of radioisotopes to engineering research for developing chemical engineering processes or for developing better metallurgy. Radioactive materials are being used in the petroleum industry. Other uses undoubtedly will be developed as experience is acquired.

The Universities' Problem

The problem presently confronting our universities is to determine what courses should be introduced to train engineers and scientists adequately for the development of atomic energy. It is not my intention to cover the needs of additional scientific training in our universities. However, I would like to make certain suggestions concerning what might be done in the field of engineering education to qualify our graduate engineers for handling nuclear engineering problems. Just one course in our engineering schools will not be the answer; what *is* necessary is the introduction of nuclear engineering courses in the several fields—civil, mechanical, electrical and chemical engineering. Such courses in their respective fields should stress the problems of heat exchange, metallurgy and materials, chemical engineering, gadgeteering or remote control, and industrial safety, all handled from the standpoint of how nuclear physics affects the solution of these problems when applied to nuclear engineering.

A Parallel Case in Point

The idea of making nuclear specialists out of engineers has a parallel in the case of Reed College in Portland, Oregon, which offers a course designed to make nuclear specialists out of medical doctors. The course includes reviews of physics, mathematics, and basic chemistry, introduces the student to nuclear physics, statistics, the genetic and biochemical effects of radiation, and gives him laboratory practice with radioisotopes. The National Research Council has already appointed several M.D.'s as AEC fellows to take this course at Reed College.

Most universities have already tackled the problem of training graduates for atomic energy development. Some progress has been made. Cornell, Princeton, Chicago, and practically every other large university have introduced courses in the field of nuclear engineering or engineering physics, but too many of them have stressed the research approach rather than the engineering approach.

One university's course leading to a master's degree in science, there is no question, stresses the physics, metallurgy and chemistry involved in nuclear energy. It covers all of the scientific or research fields but it apparently does little toward giving the student the engineer's concept of how to approach a typical engineering problem. The universities are making a mistake if this is to be the main educational effort. If it is the main effort, it is up to the educators in engineering to correct it.

Greater progress can be made if we train engineers to handle nuclear prob-

lems just as we have trained chemical engineers to handle chemical problems involved in the engineering, design, construction and operation of production plants. Instead of giving a few courses in engineering to a student who is essentially a physicist, a chemist, or a metallurgist, greater emphasis should be placed upon giving students who have a basic engineering education, either civil, chemical, electrical, mechanical, the principles of physics and the problems of nuclear engineering involved in the particular field of engineering. For example, a chemical engineer would major in nuclear chemical engineering, or a civil engineer major in nuclear civil engineering, each taking the necessary additional courses to qualify him for work in the field of atomic energy.

The Societies' Contribution

The American Society of Mechanical Engineers is assisting in this problem. In recent meetings of their atomic energy committee, they have discussed the need for a greater number of engineers in the atomic energy field. They have offered to assist the AEC in trying to procure more engineers with industrial and commercial background for this work. More engineers and engineering organizations will be necessary as time goes on if the basic work of the scientists presently engaged in the problem is to be properly developed and applied. The American Society of Mechanical Engineers is also preparing a glossary of all terms involved in nuclear engineering as a first step in the education of engineers. They are, in addition, entertaining the idea of making proposals for the placing of engineers in atomic energy work.

How University Personnel Can Help

In attempting to develop proper education courses, secrecy and government control of the atomic energy field may appear to be limiting factors. However, there is plenty of information available upon which an effective start in the field of education can be based. A means that bears recommendation is for more university engineering departments to seek contracts from the AEC or with its contractors for the development of the engineering research in this field. Also, more professors should seek temporary employment with the AEC and its contractors so that they can get first-hand information about the problems involved. They will then be in a better position to determine the basic educational courses in the field of physics and physical chemistry required and the revisions and additions necessary to our more standard engineering courses.

Our educational efforts in the field of nuclear engineering should be devoted primarily to giving supplementary education in the fields of physics and radioactivity to engineers rather than trying to give a little engineering to scientists. Although it is recognized that both approaches are necessary, the engineering approach to the problems of atomic energy will do far more towards expediting the solution of the remaining problems than the scientific approach. There is no mystery about atomic energy that good engineering cannot solve.

On this very important subject of nuclear engineering education . . .

readers are invited to submit discussions with a view to publication in NUCLEONICS. Address correspondence to The Editor, NUCLEONICS, 330 West 42nd Street, New York 18, N. Y.

Preparation and Use of Neutron Sources

The most common alpha neutron source is radium-beryllium. Also used are polonium sources, which have the advantage that they emit only weak gamma radiation. Properties of photoneutron sources are tabulated. In using neutron sources containing radium, protection of personnel against gamma radiation is more important than against neutrons

By K. J. McCALLUM

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THE DEVELOPMENT of the cyclotron and the chain-reacting pile has made available the intense sources of neutrons which are required for many investigations. For many purposes, however, much smaller neutron intensities are sufficient. Here sources may be used in which the neutrons are produced by a reaction utilizing the radiations from radioactive substances. These sources have the advantage that they are compact and portable, and in certain cases emit neutrons unaccompanied by intense gamma radiation. Furthermore, these sources can be made available to small laboratories which do not possess the resources of a chain-reacting pile or large machines utilizing artificially accelerated particles.

It is the purpose of this article to describe the preparation and use of these small neutron sources, and to consider some of the precautions which must be taken to provide protection against overexposure to radiations.

PREPARATION OF SOURCES

Since no suitable long-lived spontaneous neutron-emitting substance is available, it is necessary to utilize for these sources a nuclear reaction in which a neutron is one of the products. Particularly suitable reactions are those in which alpha particles or gamma rays are used to bombard the nuclei of deuterium, lithium, beryllium or boron, resulting in an (α,n) or (γ,n) reaction. Because of the small cross section for these reactions, only a very small fraction of the alpha particles or gamma rays produced by the radioactive material is used in the actual production of neutrons. The number of neutrons produced by these sources is thus much smaller than the total number of radioactive disintegrations which occur.

Alpha Neutron Sources

The most commonly used alpha neutron source makes use of the reaction between an alpha particle and beryllium for the production of neutrons. The nuclear reaction occurring is

$$_4Be^9 + {}_2He^4 \rightarrow {}_6C^{12} + {}_0n^1$$

It is found (*1*) that some of the neutrons emitted in this reaction have energies which may be resolved into groups. In addition there are large numbers of slow neutrons which cannot be resolved. The energies of the neutrons also depend upon the energies of the incident alpha particles. Sources

such as these are thus not suitable for the production of monoenergetic neutrons.

The alpha particles emitted from polonium, radium, radon and radiothorium have been successfully used for the production of neutrons through this type of reaction. The use of polonium sources has the distinct advantage that gamma rays are practically absent, there being produced only about one photon per neutron. This may be desirable in the study of processes in which gamma rays could cause complicating reactions. It also simplifies the problem of providing protection for the experimenter against the action of radiation from the sources which are being used. On the other hand, sources utilizing radon and radium emit an intense gamma radiation along with the neutrons, which is a distinct disadvantage.

In the preparation of sources using radon to provide the alpha particles, the procedure is simply to seal radon gas in a tube containing beryllium powder. For maximum efficiency in the production of neutrons, certain precautions must be taken (*2*). Since the neutrons are produced only when alpha particles strike the metal, it follows that the fraction of the alpha particles which strikes the wall of the containing vessel should be kept as small as possible. It has been shown that no significant amount of radon is adsorbed on the surface of the beryllium grains, so that the radon gas is distributed nearly uniformly over the gas volume between the granules and in the dead space above the powder in the sealed-off tube. A large fraction of the alpha particles emitted by the radon in the gas volume at the top of the container will strike the walls and so not contribute to the production of neutrons. For maximum efficiency, then, the tube should be filled as full as possible with beryllium powder, and the dead space above should be kept to a minimum. This makes it necessary to seal off the containing tube very close to the surface of the beryllium metal. As long as the dead space volume is maintained at the same fraction of the total gas volume, the neutron-producing efficiency appears to be almost independent of the weight of beryllium metal in the range from 0.1 to 1.5 grams (*2*).

It is also important that the beryllium used be of high purity. The passage of the alpha particle through an impurity present in the material may cause a reduction in its energy, and since the yield of neutrons depends upon the energy of the alpha particles, a considerable decrease in efficiency may result. It has been reported (*2*) that replacing high purity beryllium powder by an oxidized sample containing only 75% beryllium by weight can reduce the efficiency of neutron production to about one half. Since the ranges of alpha particles in solids are of the order of 20–30 microns, even much smaller amounts of oxide, particularly when present as a thin surface layer, may have considerable effect.

The geometrical shape of the source is of minor importance (*2*). The influence of the shape of the container upon the number of neutrons produced will depend upon the variation in the ratio of the numbers of alpha particles striking the beryllium granules and the containing vessel. Since the surface area of the walls of the vessel will, in general, be small compared to the surface area of the beryllium granules, the fraction of the alpha particles striking the walls is small in a suitably filled source, unless tubes of very thin cross section are used.

The yield of neutrons is thus dependent upon the care used in the preparation of the source. In general, these sources give 10,000–25,000 neutrons per sec per millicurie of radon.

Radon sources suffer from the dis-

advantage that the neutron-producing efficiency decreases with the decay of the radon. The use of radium instead of radon produces a source which emits neutrons at a rate which, for all practical purposes, can be considered constant. Under ideal conditions it might be expected that the yield of neutrons from a radium source would be greater than that from a radon source of equal curie strength because of the one more alpha particle available. However, in practice, it is found that, per millicurie, a radium-beryllium source emits only about 75% as many neutrons as does a radon-beryllium source (*3*). This decrease in the number of neutrons emitted is attributed to the loss in energy which the alpha particle suffers in escaping from the crystal of the radium salt. The smaller the crystal size of the radium salt, the smaller will be this effect. The ideal conditions would be attained if the radium salt could be deposited in a monomolecular layer on the surface of beryllium granules which were tightly packed. This condition is not readily attained. The use of the sulfate of radium rather than the chloride or bromide has been suggested (*2*), because the crystal size is usually smaller.

The source is prepared by evaporation of a solution of a radium salt containing beryllium powder in suspension. If the radium salt is insoluble, as is so for the sulfate, both the salt and beryllium powder will be in suspension, and the mixture must be thoroughly stirred during the evaporation process. Needless to say, during the evaporation and drying stages, obvious precautions must be taken for the protection of the operator. The dried powder may then be placed in metal tubes of either brass or steel, and a cap securely sealed on. If desired, the powder can first be sealed in a glass tube, which should then be placed in a protective metal container.

With sources in which the beryllium is present as a loose powder, a small change in neutron output may sometimes be observed due to movement of the beryllium powder. Anderson and Feld (*4*) have described the preparation of sources in which this does not occur. After evaporation of a solution of radium bromide containing beryllium powder in suspension, the resulting preparation is compressed in a hydraulic press, using pressures of the order of ten tons per square inch. The pellet is then placed in a brass container and the cap sealed on with soft solder.

The preparation of such sources may be outlined as follows:

1. The radium salt is dissolved in water and allowed to stand in a hood for at least 12 hours to remove the radon gas.

2. The required amount of beryllium is added to the solution in the form of a fine powder (325 mesh) of the metal. A small amount of pure alcohol may be added to decrease the surface tension and allow the powder to be wet by the water.

3. The solution is then evaporated to dryness, first over a Bunsen flame and finally on a hot plate or steam bath. The mixture should be stirred frequently to prevent the formation of lumps. The mixture is finally heated to a temperature of 150–200° C for an hour to remove the water completely.

4. The dry mixture is powdered and then poured into a steel die. The powder is pressed in a hydraulic press, using a pressure of about ten tons per square inch. The compact pellet which results is capable of withstanding a moderate amount of handling.

5. The pellet and excess material from the sides of the die are placed in a brass container, the lid screwed on and the container sealed with soft solder. The containers should be designed so as to provide for a slight expansion of the pellet which occurs after the pressure is removed. It is convenient to have

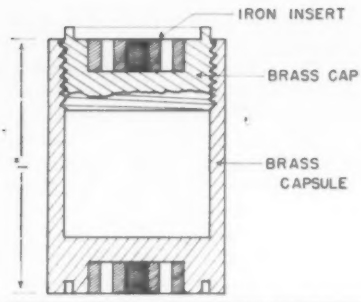

FIG. 1. Capsule for compressed Ra-Be sources

a threaded hole in the cap to allow handling of the source. If frequent handling is required, it is desirable to have an iron insert in the cap in which the threaded hole is placed, since brass threads wear out if used too much. The iron insert also permits magnetic handling of the body.

An example of a container designed for one gram of radium and three grams of beryllium is shown in Fig. 1 (*21*). This consists of a brass cylinder fitted with a brass cap in which an iron insert is brazed in place. In the iron insert is a central threaded hole and two other drilled holes. A similar iron insert is placed in the base of the brass container. This permits two sources to be screwed together in a reproducible manner using a threaded brass stud.

A rod which can be used for carrying such sources (*21*) is shown in Fig. 2. It consists of a hollow brass rod fitted at one end with two shims which fit into the two drilled holes in the iron insert on the source. This serves as a wrench to hold the source while a solid threaded rod, passing through the hollow brass cylinder, is screwed into the threaded hole in the iron insert. This rod should be about one meter in length to provide for a safe distance between the source and the operator.

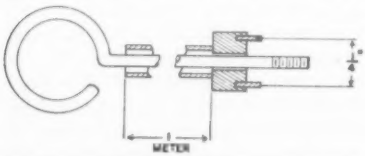

FIG. 2. Holder for compressed Ra-Be sources

The soldering of the source may be done in the following manner (*21*): The threads on the capsule and caps can be completely tinned before the source is inserted. After the source is assembled, the capsule should be heated on a hot plate until the solder on the threads melts. More solder can be added, and the cap screwed up and down a few times and then allowed to cool.

Sources have been prepared in this way containing as many as five grams of radium and 25 grams of beryllium. Since the density is increased to about 1.75 grams per cc by the compression, a large decrease in volume results, and these sources are very compact compared to those containing loose beryllium powder. They thus have the additional advantage that they can more closely approximate point sources in cases where such are desired.

The neutron yield of sources prepared in this way is found to depend somewhat upon the ratio of the weights M of radium salt and beryllium powder used in the preparation. Anderson and Feld (*4*) give the following expression for the yield of neutrons:

$$\text{Yield} = 1.7 \times 10^7 \frac{M_{Be}}{M_{Be} + M_{RaBr_2}} \text{ neutrons/sec/gm Ra}$$

Sources prepared from polonium have the advantage that the gamma radiation which is emitted is much less intense than that from radon or radium sources. The polonium used in these sources is often obtained from old radon residues, in which the polonium appears as a decay product. Procedures for the separation of polonium from these residues have been described (*5*). For

maximum efficiency of these sources, it is highly desirable that the polonium be obtained free from macroscopic quantities of impurities which may absorb or decrease the energy of the emitted alpha particles.

Early polonium neutron sources were prepared by depositing the polonium from solution on one side of a nickel or silver disk. Another disk of beryllium or boron was then placed facing the polonium deposit. Neutrons from such sources are emitted principally from one side only, so that an asymmetric distribution of neutrons about the source is obtained.

An alternative is to deposit the polonium on both sides of a silver or nickel disk which is then placed between two sheets of beryllium metal. The distribution of the emitted neutrons from this source is also somewhat asymmetric, the greatest emission of neutrons coming from the disk faces.

In these types of sources, about one half of the alpha particles emitted by the polonium passes into the nickel or silver disk. They are absorbed there and are not utilized for the production of neutrons. It is observed also that the neutron production from these sources decays at a rate somewhat faster than that expected from the decay of the polonium. This is ascribed to the gradual penetration of part of the polonium into the silver or nickel disk, so that more than half of the emitted alpha rays are lost by absorption.

Polonium may be deposited directly from solution upon the surface of beryllium powder by evaporation or chemical deposition (*6*). A method is described in which the polonium is precipitated by sodium hydrosulfite upon the inside of a tube prepared by drilling a hole in a cylinder of beryllium. The tube is then filled with beryllium powder, and closed at the top with a glass stopper, sealed to the tube with picein. In this way, sources are prepared (*6*) in which the neutron production is very nearly double that of sources prepared by deposition on a silver or nickel disk.

Photoneutron Sources

Neutron sources have been prepared utilizing the reaction between a gamma ray and the nucleus of deuterium or beryllium, in which a neutron is ejected. For this process to occur, the energy of the incident gamma ray must exceed the binding energy of the neutron in the primary nucleus. There is thus a threshold value for the gamma ray energy, a neutron not being ejected if the energy of the gamma ray is less than the threshold value. The values of the threshold for deuterium and beryllium are 2.18 Mev and 1.63 Mev, respectively.

Photoneutron sources are particularly important because, if gamma rays of a single energy are used, a nearly monoenergetic source of neutrons is produced. The excess energy of the incident gamma ray over the threshold value is distributed over the products of the reaction, the neutron and the product nucleus, in a manner determined by the laws of conservation of energy and momentum. A small spread in the energy of the emitted neutrons results because of the different possible angles between the direction of the incident gamma ray and the path of the ejected neutron (*7*). Since it is now possible with the chain-reacting pile to prepare many gamma-active isotopes of high specific activity, each emitting gamma rays of definite energy, small monoenergetic sources of neutrons can be made available.

The cross section for the (γ,n) reaction is, in general, so small that absorption of the gamma rays is far from complete and the unreacted gamma rays are emitted along with the ejected neutrons.

The photoneutrons ejected from

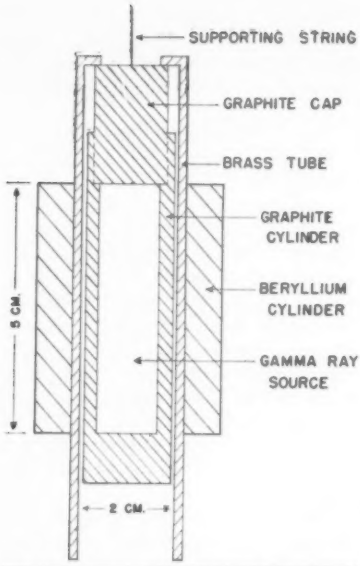

FIG. 3. A photoneutron source

deuterium and beryllium by a variety of gamma-emitting isotopes have been investigated by Wattenberg (*7*), and by Russel, Sachs, Wattenberg and Fields (*8*). The isotopes studied by them were some of those which could be produced by the (n,γ) reaction in the chain-reacting pile. The gamma-ray source was produced in the pile in a cylindrical graphite container. For the preparation of the photoneutron source, the gamma emitter was placed inside a thin-walled brass tube around which was mounted a cylinder of beryllium or a brass container of heavy water. Figure 3 shows a diagram of a photoneutron source practically identical with that used by these authors. The energies of the photoneutrons were determined by measurement of the scattering cross sections in paraffin, and the number of neutrons was obtained by comparison with a standardized Ra-α-Be source.

It was found that some loss in the energy of the neutrons resulted from collisions with nuclei inside the source itself. The neutron velocity distribution was broadened on the low energy side. It was estimated that, with sources of the dimensions which were used, an average decrease in energy of about 20 percent resulted. The amount of broadening due to this factor would, of course, be less with smaller sources.

The number of neutrons emitted depended upon the energy of the gamma ray and upon the geometrical dimensions of the source. From the experimental data, estimates were made of the neutron emission of a "standard" source, which consisted of one curie of a radioactive material placed at a distance of one centimeter from one gram of target material. The number of neutrons emitted by sources of the actual geometry and dimensions used were ten to twenty times as great. The uncertainties in the absolute values of neutron yields were placed at 27 percent, although the relative values should be more reliable.

The properties of some of the sources which were studied are shown in the table below.

Properties of Photoneutron Sources

Gamma-emitting Isotope	*Target*	*Half-life*	*Energy of Neutrons* (Mev)*	*Neutron yield of standard source per sec per curie*
Na^{24}	D_2O	14.8 h	0.27	29.0 $\times 10^4$
Na^{24}	Be	14.8 h	1.00	14.0 $\times 10^4$
Ga^{72}	D_2O	14 h	0.16	6.9 $\times 10^4$
Ga^{72}	Be	14 h	—	5.9 $\times 10^4$
Sb^{124}	Be	60 d	0.029	19.0 $\times 10^4$
La^{140}	D_2O	40 h	0.16	0.68 $\times 10^4$
La^{140}	Be	40 h	0.75	0.23 $\times 10^4$

* Estimated for a very small source.

Of these sources, which can be prepared using pile-irradiated material, that produced from antimony should prove particularly useful. It furnishes a good yield of neutrons and the long half-life of sixty days makes available a source which decays at a rate not inconveniently fast.

Gamma-emitting substances other than those produced in the pile may, of course, also be used in the preparation of photoneutron sources. An isotope of yttrium produced by deuteron bombardment of strontium has a half-life of 87 days and emits a gamma ray of sufficient energy to dissociate beryllium, with the formation of neutrons of 0.16 Mev. The gamma rays of radium, radon and radiothorium have also been used.

Production of Slow Neutrons

For many purposes it is desired to use the neutron source as a source of slow neutrons, *i.e.*, neutrons with thermal energies. It has long been known that neutrons may be slowed down effectively through collisions with nuclei of low atomic weight. In choosing a slowing-down medium, it is necessary that the nuclei have a low cross section for the absorption of neutrons, so that the number of neutrons lost through capture will be small. Collision of the neutrons with the protons in paraffin or water is the method most commonly used for the production of slow neutrons.

In general, the neutron source is placed at the center of a paraffin block or enclosed in a water-tight container and immersed in a vessel containing water. The neutrons which are emitted are slowed down by collisions with protons until their velocity approaches thermal velocity corresponding to the temperature of the slowing-down medium. Approximately twenty collisions are necessary to reduce fast neutrons to thermal energies. One obtains what is essentially a gas of slow neutrons,

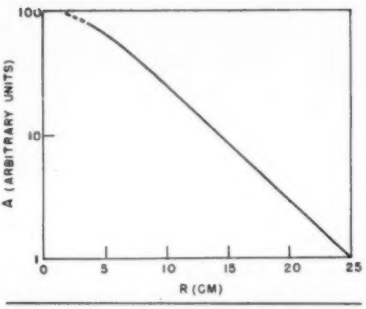

FIG. 4. Saturation activity A induced in a detector as a function of the distance R from a source immersed in a large tank of water

with a source at the center, and with some of the neutrons being captured by nuclei throughout the medium. After about 140 collisions, a neutron will be captured by a proton (*9*).

The mean free path of the neutrons depends upon their energies, the average distance between collisions decreasing as the energy is lowered. At the high energies the mean free path is several centimeters, while thermal neutrons have a mean free path of a few millimeters. The neutrons are not all passing in an outward direction, but diffusion of thermal neutrons occurs throughout the medium.

The number of slow neutrons that can be obtained in a given volume of the medium depends upon the rate of production of slow neutrons and upon the rate of absorption of slow neutrons by the medium. The neutron flux, the number of neutrons passing per second through 1 sq cm of area in the medium, may be determined using detectors of known cross section, such as rhodium, indium or manganese foils. When a Ra-α-Be source is placed in a large tank of water, it is found that the neutron flux is highest at small distances from the source. With increasing distance from the source the neutron flux decreases slowly, and then at a

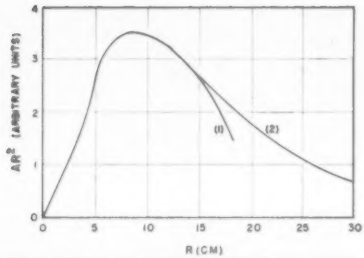

FIG. 5. The value of AR^2 as a function of the distance R from a source immersed in water (1) in a cylindrical tank 38 cm in diameter, (2) in a tank 100 × 100 × 75 cm

distance of 8 or 9 cm from the source, the neutron flux drops off exponentially. This is shown in Fig. 4, where A, the saturation activity induced in a detector, is represented on a semi-logarithmic plot as a function of R, the distance from the source to the detector. In this region, the relaxation length, the distance through which the flux drops to one eth of its value, is about 9.3 cm (*10*). A plot of neutron flux times the square of the distance from the source has a maximum at a distance of 9 to 10 cm.

The neutron distribution in water depends somewhat upon the size of the tank containing the water. For example, Bakker (*11*) has measured the neutron distribution about a source in a small cylindrical tank 38 cm in diameter and also in a tank 100 cm × 100 cm × 75 cm. The results are shown in Fig. 5, where AR^2 is plotted against R. In both cases, the neutron distribution was almost identical up to distances of 15 cm from the source. Beyond this distance, the neutron flux was greater in the larger tank due to those neutrons which had diffused back from larger distances. For most slow neutron irradiations, using water as the slowing-down medium, a tank 30–40 cm in diameter is sufficient.

When paraffin is used as the slowing-down medium, the source may be placed in a hole at the center of a paraffin block 20–30 cm in diameter and 15 cm high. Small amounts of material to be irradiated may be placed in holes in the paraffin surrounding the source. The cylinder is then covered with a paraffin cover about 5 cm thick.

Using silver and indium detectors, Yost and Dickinson (*12*) have investigated the neutron distribution about a source placed at the center of a paraffin sphere as a function of the distance from the source and of the diameter of the wax sphere. Within the sphere, they found that the activity produced in a detector placed at a given distance from the source increased up to a maximum value as the radius of the sphere was increased. This was because of neutrons which had diffused back to the detector. The activity detected at a distance of 10 cm from the source attained about 90% of its maximum value when the radius of the sphere was 17.5 cm. Higher activities with smaller paraffin spheres can be obtained at distances closer to the source, although fast neutrons will also be present at such positions.

When it is desired to irradiate large volumes of liquids, the source may be placed in a glass tube and immersed in the liquid. If the compound contains hydrogen, it may act as its own slowing-down medium. A layer of paraffin placed around the vessel containing the liquid may be used to reflect some of the slow neutrons and so increase the neutron flux. Of course, in such arrangements, large numbers of fast neutrons will also be present. If the experiment is such that this is undesirable, a layer of paraffin can be placed directly around the source.

The characteristics of neutrons leaving the surface of a paraffin block, inside which a source is placed, have been studied by many investigators. If the radius of a paraffin sphere surrounding the source is small, the number

of slow neutrons emerging from its surface is likewise small, since the thickness of the paraffin is insufficient to permit many collisions of neutrons with protons before the neutrons escape from the surface. With increasing radius of paraffin, the number of slow neutrons leaving the surface increases to a maximum, after which a decrease occurs due to capture of neutrons within the paraffin. The maximum number of slow neutrons per unit solid angle is emitted when the radius of the paraffin sphere is about 10 cm (*13*). The same value has been reported for the neutrons emerging from a source surrounded by cylindrical layers of water (*14*). Experiments have indicated that the velocity distribution of the neutrons emitted from the surface is nearly Maxwellian.

More intense neutron beams can be obtained from a given source if the paraffin is shaped so as to form a neutron "howitzer" (*14*, *15*), which has a hole in the paraffin block pointing towards the target. By taking advantage of the backscattering of neutrons which were initially directed away from the target and the reduction in scattering of those directed to the target, beams three to five times the intensity of those which can be obtained from the surface of a paraffin sphere can be produced. A copper block can be placed, as shown in Fig. 6, to scatter the fast neutrons which come directly from the source and which would make only a few collisions with the paraffin.

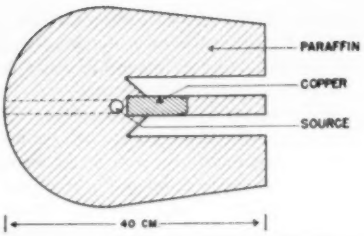

FIG. 6. A neutron "howitzer"

PRACTICAL PRECAUTIONS

When neutron sources are used in the laboratory, consideration must be given to the problem of protection of the operator from the emitted radiation (*16*). This is especially important when the sources contain gamma-emitting materials, since protection against gamma radiation constitutes a more serious problem than does protection against the neutrons which these small sources emit.

When radium-beryllium sources are being used, it is very advisable that tests be conducted to ensure that no leakage of radon gas is occurring. The escape of radon gas from the capsule would not only constitute a serious health hazard, but could also cause radioactive contamination of any materials under irradiation. The test can be carried out very easily by placing the source in a glass tube and then inserting a plug of absorbent cotton. After at least twelve hours, the cotton is removed and tested for radioactivity with a sensitive electroscope or a Geiger counter. Small leaks resulting in the release of as little as one microcurie of radon can be detected in this manner.

During actual manipulation of the source while assembling the apparatus, the inverse square law is of prime importance. Since the intensity of the gamma radiation is inversely proportional to the square of the distance from the source, the use of forceps, tongs or other special tools is required to reduce the possibility of injurious radiation. Increasing the distance between the source and the operator from 1 cm to 100 cm, through the use of long-handled tongs, decreases the amount of irradiation per unit time by a factor of ten thousand. Thus, in terms of a maximum permissible exposure of 0.05 roentgens per 8-hr day (*17*), 250 mc of

radium would produce the tolerance dose at a distance of 1 cm in about $\frac{1}{12}$ sec, while at a distance of 100 cm, the time is about 14 minutes.

If the source is encased in a magnetic material, such as stainless steel, or if a piece of iron is securely sealed to a brass capsule, an electromagnet on the end of a rod furnishes a tool that is, in many operations, more convenient to manipulate than long-handled tongs. It is particularly useful for inserting or removing the source from narrow glass tubes in which it may be placed for the irradiation of liquids.

During the preparation of the source and material for bombardment, the health hazard comes from short and relatively intense exposures. When the experiment is under way, the greatest danger is from long-continued irradiation of low intensity. Situations may easily arise where the danger of overexposure to gamma radiation is less for the individual actually using the source than for other persons in the vicinity. In planning gamma-ray protection, the occupants of the rooms above, below and on all sides of the radioactive material must be considered.

In addition to having the source sufficiently far removed from positions where other personnel are working, it is usually necessary to have a certain amount of absorbing material in the path of the rays. The material usually employed for this purpose is lead. A chart has been prepared by Failla (*18, 19*) which shows the combinations of distance and lead screening necessary for adequate protection from varying amounts of radium. This chart shows, for example, that about 5 cm of lead screening will serve as protection from 250 mc of radium at a distance of 1 meter. The amount of shielding required depends upon the energy of the emitted gamma rays. Tables have recently been published (*20*) from which the thicknesses of material required to shield against gamma rays of various energies can be determined. These tables are particularly useful for photoneutron sources.

In addition to providing protection from the direct gamma radiation from the source, consideration must also be given to radiation scattered back into the room from the walls and floor. Since the amount of scattered radiation at any point depends upon the geometry of the room, it is very advisable that the safety of the existing installation be tested. This can be done in various ways (*19*), for example, by the use of a hand fluoroscope or films. More convenient and rapid is the portable gamma count-rate meter, types of which are available commercially. This instrument gives a rapid measurement of the gamma-ray intensity in terms of roentgens, and is extremely useful in the rapid location of health hazards.

When gamma-emitting neutron sources are used for slow-neutron irradiations and are adequately shielded for protection against gamma radiation, protection from the neutrons which are emitted does not constitute a serious problem. The distance from source to operator which is necessary for gamma-ray protection is adequate also for neutron protection from these small sources. The maximum permissible exposure to thermal neutrons is that given by a flux of 750 neutrons per cm^2 per sec for 8 hrs per day (*17*). This is the flux that one would calculate at a distance of about 30 cm from a radium-beryllium source containing 1 gm of radium, assuming that no neutrons were lost by absorption in the materials surrounding the source, and that no backscattering occurred. For experimental installations, the neutron flux is very much less than that required to give the maximum permissible exposure at distances of 1 meter from the source.

For fast neutrons, the maximum permissible exposure is that given by a

flux of 100 neutrons per cm^2 per sec for an 8-hr day (*17*). This, too, is larger than the flux at a distance of 1 meter from a 1 gm radium-beryllium source emitting fast neutrons. With polonium-beryllium sources, even though extensive gamma-ray shielding is not necessary, due regard must still be paid to the neutron flux at small distances from the source.

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Engineering Problems in Atomic Energy

PROBLEMS that must be solved before atomic energy can be made useful are largely engineering. The machines (reactors) must run at high temperatures in order to extract the energy in useful form, and this means there will be problems involving materials of construction. Construction materials also must be chosen from those whose neutron absorption is small, and this limits the choice to uncommon substances.

Adequate coolants which do not absorb neutrons must be found and a method for control of the reactions must be assured. It will also be necessary for the chemists and chemical engineers to develop very efficient procedures to purify the plutonium and uranium and also to repurify these materials in order that unburned fuel may be used again.

The staggering amount of radiation emanating from the pile operating at a high power level makes it necessary to enclose the power pile within thick walls of concrete, steel or other absorbing material. And this creates other problems, for shielding material must be so constructed that the pile may be loaded and unloaded and the coolant carried in and out. Yet the shields must be not only radiation tight, but air-tight, since air exposed to the radiation of the pile would become radioactive.

—from a talk by Glenn T. Seaborg, at meeting of American Society of Mechanical Engineers, June 29, San Francisco

CLASSICAL RADIOACTIVITY, 1940–1949

By N. FEATHER

Department of Natural Philosophy, University of Edinburgh, Scotland

IT IS AXIOMATIC that our ability to add continually to our knowledge of the modes of transformation of the classical radioelements, after half a century of concentrated study of their behavior, derives both from the fundamental complexity of the disintegration possibilities for a great many of these elements and from the steady progress which continues to be made with new methods of investigation. It is worth while listing the more important of these new and powerful methods before considering in detail the information which has been obtained by their use. The latter is listed and arranged in order under the symbol of each of the classical radioelements in turn.

Alpha-particle Spectrum Analysis

In relation to α-disintegration, the primary requirement is still a method of high resolution for the analysis of the energy spectrum (line spectrum) of the disintegration particles, and when sources of sufficiently great specific activity are available no method bears serious comparison with the method of semicircular focusing, first successfully applied in this field by Rosenblum (*138*) in 1929. But for many of the classical radioelements sufficiently intense sources are not available (for the longest-lived elements, such sources can never be available, in the nature of the case), and then the range method has been used. This method is essentially limited, as to resolving power, by the straggling of the ranges.

When standard air ranges are determined, the differential ionization chamber of Rutherford, Ward and Wynn Williams (*145*) is best employed, but with the longest-lived elements, if the air equivalent thickness of the source is to be no greater than the linear straggling coefficient for the α-particles which it emits, serious problems of intensity are again encountered.

The determination of track lengths in photographic emulsions is not attended by these difficulties regarding source thickness and intensity, but until recently the straggling of the first-to-last grain distance (track length) has been inconveniently large and, in consequence, the resolving power of the method has been poor. That this is no longer so is due to the introduction of new "nuclear" emulsions of very high silver content and very small grain size (*129*). With these emulsions significant advances in range determination have been made.

These advances, however, have to some extent been overshadowed by another advance in a different direction. Range straggling is a reflection of fluctuations in the distribution of the primary ionizing events occurring along the path of the α-particle. Straggling in the total ionization (primary plus secondary ionization) produced by the particle is clearly relatively less in amount.

A distribution curve of amounts of total ionization is therefore better suited than a distribution curve of ranges for α-particle spectrum analysis. That distribution curves of the former

The author of this extensive review article, Professor N. Feather, F.R.S., F.R.S.E., has recently been appointed a member of the Radioactive Substances Advisory Committee which serves four British Ministries. Author of the text, "Introduction to Nuclear Physics," published in 1936, he is today, by virtue of his pioneer work in the field, a most distinguished and competent judge of recent progress in classical radioactivity.

In this review, he confines his attention strictly to experimental work on the radioactivity of uranium-238, uranium-235, and thorium-232 — and their natural decay products — published since January 1, 1940. In the main, he considers only such results as provide fresh information regarding modes of transformation specific to the species involved. Only occasionally does he touch on the recent work on secondary effects which occur with active bodies in general, and in no instance does he refer to experiments in which the "classical" radioelements have been used as sources of radiation for disintegration studies, or as tracers in problems of applied radioactivity.

type can now be derived by direct experiment is due to the development of the "fast," "gridded," ionization chamber, and to the perfection of electronic amplifiers giving "linear" amplification of incoming pulses. The addition of the electronic pulse analyzer to such equipment makes the whole experimental arrangement almost self-operating (*26*, *63*). In this connection the fact should not be lost sight of that the fast ionization chamber utilizes successfully one half of the total α-particle emission from any source and that the permissible source area is not severely restricted. Therefore, no serious intensity problems arise, even with the α-emitters of longest life. Also, the fast chamber can obviously be employed as a counting chamber pure and simple, and when it is used in this way the problem of the determination of the lifetimes of the long-lived α-emitters becomes essentially a problem in gravimetric chemistry rather than a problem in nuclear physics.

Beta-particle Spectrum Analysis

In β-particle spectrum analysis, difficulties will always be greater than in α-particle spectrum analysis just because the fundamental spectral components are the partial continuous spectra of β-disintegration rather than the discrete monokinetic groups which characterize α-disintegration. But the distinction between those radioelements which can be dealt with by magnetic spectroscopy and those for which sufficiently strong sources are not available, and which must therefore be examined by the absorption (range) method, still applies. Improvements in the design of magnetic spectographs have resulted in increases in collecting power (*36*, *93*, *132*, *134*, *155*, *165*, *166*, *167*), broadening their range of applicability, but the refinements which have been introduced into the use of the simple absorption method (*9*) have been equally productive of new knowledge concerning individual β-emitters.

The full power of techniques based upon coincidence counting has also become widely recognized during the past ten years, and it is now generally agreed that apart from these techniques there is no purely objective method of analysis of complex β-spectra (*47*). The success of the method of coincidence counting depends, of course, upon the time-correlation which naturally obtains as between the emission of disintegration electrons and γ-ray quanta

(or "natural" photoelectrons) from individual atoms. The method itself may be used in absorption studies (*39*, *122*) or in investigations in which magnetic analysis is employed, the most powerful mode of application being clearly that in which the correlations between the photoelectrons of one particular spectrum line and the disintegration electrons in a single narrow range of momentum are examined (*54*).

If this chosen momentum range may be taken anywhere in the continuous spectrum, in theory at least a complete picture of the complex β-γ process can be obtained. So much is certainly true "in theory," but this type of analysis will not always be possible in practice and it is likely that many cases will long remain in which the "complete" picture is lacking, even when attention is confined, as it is in this review, to the β-emitters among the classical radioelements.

If we arbitrarily define the "complete" picture as one in which the intensities of all partial β-spectra are known within a probable error of ± 0.03 (per disintegration) it is doubtful whether at the present time such completeness can be claimed except for UX_2, RaE, AcC'' and, possibly for ThB and ThC. This statement provides a measure of the amount of work which remains to be done on the β-emitters of the classical series—particularly since it will be obvious that our arbitrary definition of completeness leaves it far from the ideal of full information.

Until very recently the photographic emulsion track method was inapplicable to problems of β-disintegration just because no emulsion had been developed in which the tracks of individual β-particles, even β-particles of low energy, could be recognized with certainty. That is no longer the case (*7*, *160*). Experimental emulsions are now in use in which the tracks of β-particles of minimum ionization are well developed (*8*), and we can look with confidence to important applications of the method, even with the classical β-emitters.

The position in regard to the pulse ionization chamber method of energy measurement is strikingly similar to that for β-sensitive emulsions. Until recently the problems of ionization chamber and circuit design involved in the "linear" amplification of pulses originating in amounts of ionization from, say 10 or 20 ion-pairs to 1,000 or 2,000 ion-pairs were regarded as effectively insuperable. Now these problems have been solved (*35*, *90*, *131*). In principle, the analysis of the energy spectrum of the β-particles emitted by any radioelement which can be admitted as a gas into a proportional counter can be carried out as an analysis of pulse sizes. An automatic "kicksorter" or pulse analyzer can provide what further "refinement" may be desired.

Gamma-ray Spectrum Analysis

At this stage no detailed consideration of the problem of γ-ray spectrum analysis need be added to what has already been said. It is true no doubt that methods involving the investigation of the various types of "excited" electron spectrum ("external" photoelectron and Compton electron spectra) have in recent years been more widely used than previously, but these methods, like the standard method of analyzing the "natural" photoelectron spectrum, almost invariably involve the magnetic analysis of β-particle energies, and gain in power as a result of every improvement in resolving power or collecting power of β-particle spectrographs. Only it should be stated that the methods of the excited spectrum are generally indispensable if precise knowledge of γ-ray intensities is sought.

Uranium-238 (U_I). The standard air range (15° C, 760 mm Hg pressure) was redetermined, with reference to the range of polonium α-particles, using a pulse ionization chamber in a novel technique by Wytzes and van der Maas (*188*), as 2.70 ± 0.01 cm.

Resolution of the α-particles of U_I from the naturally accompanying α-particles of U_{II} (see below) by the photographic emulsion range method was first achieved by Powell (*128*) using Ilford half-tone emulsions. Histograms showing the two groups resolved with Ilford concentrated (B1) emulsions were given by Green and Livesey (*66*) and, for similar emulsions (C2), they (*67*) determined the mean range of the particles from U_I as 16.0 ± 0.2μ. Faraggi (*46*) obtained the value 15.5 ± 0.2μ from Ilford concentrated half-tone plates.

Clark, Spencer Palmer and Woodward (*27*) compared the mean pulse sizes due to the U_I and Po α-particles in a gridded argon-filled ionization chamber and deduced a value of 4.180 ± 0.015 Mev for the U_I α-particle energy. These authors conclude that their energy value points to a mean air range of 2.69 ± 0.02 cm, and the emulsion range of Green and Livesey is consistent with this, in that the two values give a point on a smooth (air/emulsion) range curve. Thus all this recent work is concordant.

Determinations of the period by α-particle counting and gravimetric chemistry are complicated in the case of U_I by the presence in ordinary uranium of U_{II} and U^{235}. The currently accepted value is 4.51 × 10^9 years [Kovarik and Adams (*94*)].

Uranium X_1 (UX_1). The definitive work on the β- and γ-radiations to date is certainly that of Bradt and Scherrer (*15*). Partial β-spectra with maximum energies 0.205 ± 0.010 and 0.112 ± 0.010 Mev, and relative intensities roughly as 4:1, were deduced by magnetic analysis, and a γ-ray of energy 93.0 ± 0.5 kev and estimated quantum intensity 0.15 were established from "natural" photoelectron and absorption studies. These component β- and γ-radiations might well be regarded as giving a "complete" picture of the disintegration possibilities, but the authors also found a γ-ray of about 180-kev energy emitted with absolute intensity roughly 0.045. The attribution of this radiation to UX_1 is more difficult to accept.

In so far as the maximum β-particle energy is concerned, the result of Jnananda (*81*) (190 kev) is in reasonable agreement with that just quoted. The half-life was redetermined by Knight and Macklin (*91*). Their value of 24.10 ± 0.02 d supports Sargent's (*149*) (24.1 ± 0.2 d), improving considerably on its accuracy.

Uranium X_2 (UX_2). Bradt and Scherrer (*14*) assign an intensity of 0.98 to the main β-particle spectrum of maximum energy 2.32 Mev and postulate a partial spectrum of intensity 0.012 and maximum energy about 1.37 Mev as the next most intense. The presence of this low-energy spectrum is deduced from the observation of a weak γ-ray of energy of the order of 0.95 Mev. Both this γ-ray and a still weaker one of about 1.5 Mev quantum energy cause no difficulties of interpretation, but Feather and Richardson (*55*) drew attention to the difficulties which attach to the problem of the highly converted (and possibly "long-lived") γ-rays of energy 0.782, 0.806 and 0.822 Mev, the *K*- and *L*-conversion lines of which Bradt, Heine and Scherrer (*12*) found to have a total intensity of 0.0055 per disintegration. The provisional conclusion of Feather and Bretscher (*53*) that UX_2 is the metastable isomer of the UX_2-UZ pair received further support by the observation of Bradt and Scherrer (*14*) of *L*- and *M*-conversion electrons of a γ-ray of 0.394 Mev energy. No *K*-conversion electrons could be detected (detec-

tion limit about ⅓ of L-conversion line intensity). As pointed out by Bradt and Scherrer, this observation is in accord with theoretical expectation if the spin difference between the isomeric states is 5 quantum units—a value deduced from considerations of the partial disintegration constant characterizing the change (branching ratio about 1.4×10^{-3}).

Uranium Z (UZ). The β-rays of UZ were studied in the semicircular focusing spectrograph for the first time by Bradt and Scherrer (*14*). The main partial spectrum (intensity 0.9) was found to have a maximum energy of 0.45 ± 0.03 Mev. A high-energy component (intensity 0.1) of maximum energy about 1.2 Mev was also indicated in the analysis. Cascade γ-rays of nearly equal quantum energy (0.75 ± 0.05 Mev) were shown to follow the β-particles of the main spectrum. The total disintegration energy $UZ\text{-}U_{II}$ is thus 1.95 ± 0.1 Mev—and the assumption that the energy difference $UX_2\text{-}UZ$ is 0.394 Mev is still further confirmed [2.32 − (1.95 ± 0.1) = 0.37 ± 0.1].

Uranium-234 (U_{II}). The standard air range of the U_{II} α-particles was given by Wytzes and van der Maas (*188*) as 3.258 ± 0.005 cm, the concentrated half-tone emulsion range by Faraggi (*46*) as 18.6 ± 0.2μ, and the C2 emulsion range by Green and Livesey (*67*) as 19.0 ± 0.2μ.

Clark, Spencer Palmer and Woodward (*27*) give a value of 4.763 ± 0.015 Mev for the α-particle energy and deduce 3.27 ± 0.02 cm as the corresponding air range. In their final pulse-size histogram for samples of natural uranium, the relative intensities of the U_{II} and U_I peaks are given as 1.005 ± 0.005:1.

Macklin and Knight (*107*) investigated the soft quantum radiations from samples of U_3O_8 for which 96% of the total α-activity was due to U_{II}. They found radiations similar in properties to the L and M X-radiations of ionium and estimated the yield as between ⅓ and 2 per α-particle emitted. They attempted to explain their result as due to L (or M) ionization of the residual atom at the expense of its kinetic energy of recoil, but this explanation seems to be much too unspecific when results with other α-emitters [*e.g.*, polonium (*33*)] are taken into account. It is more probable that almost complete internal conversion of a very soft γ-ray is involved—but the form of the α-particle pulse spectrum (indistinguishable from that of U_I) obviously sets rigorous limits as to relative intensities. Possibly the α-disintegration $U_{II} \rightarrow Io$ almost always goes to a low-lying excited state of the latter nucleus. In that case the de-excitation radiation would be expected to be highly converted (and probably "long lived"). It is likely that investigations with β-sensitive emulsions will help to solve this particular problem.

Until recently, estimates of the half-life depended on measurements with natural uranium samples using the method of mass spectrum analysis [*cf.*, Nier (*119*)]; now repetitions of these measurements have been supplemented by the α-particle counting of enriched samples previously subjected to mass analysis [Chamberlain, Williams and Yuster (*21*)]. The best value appears to be $(2.33 \pm 0.10) \times 10^5$ yr.

Ionium (Io). The standard air range of the Io α-particles was redetermined by Curie and Tsien (*34*) as 3.11 ± 0.01 cm. Clark, Spencer Palmer and Woodward (*27*) estimated 3.16 ± 0.02 cm from their energy value 4.657 ± 0.011 Mev.

Preliminary measurements by Rosenblum, Valadares and Vial (*141*) using semicircular focusing indicate two close groups of energies 4.682 ± 0.010 and 4.61 Mev respectively, and relative intensities approximately 4:1, and possibly a very weak third group of lower energy. The difference in disintegration energy corresponding to the two main groups agrees well with the energy of the softer γ-ray first esti-

mated by Ward (*185*). Recent work by Curie (*32*), Teillac (*169*) and Riou (*136*) fully confirmed Ward's results and gave more precise values of $(5.0 \pm 1.5) \times 10^{-3}$ and $(3 \pm 1) \times 10^{-3}$ for the quantum intensities of the radiations of 68 kev and about 200 kev energy. The fact that the softer γ-radiation is almost completely internally absorbed (confirmed by measurements on the fluorescent *L* X-radiation by Curie and Riou) clears up a difficulty pointed out by Feather (*48*) in 1940. It is not now necessary to assume a large difference of spin between the ground state and the first excited state of the product nucleus.

Radium (Ra). The report by Chang (*23*) that the α-particle spectrum shows a many-lined fine structure has recently been withdrawn (see under Po, below).

Radon (Rn). While Karlik and Bernert (*87*) showed (on plausible assumptions regarding the α-particle energy of francium-222) that the β/α branching ratio for Rn is less than 10^{-6}:1, in a general discussion of the subject, Feather (*52*) concluded fairly certainly that Rn is a "pure α-active" species.

Radium A (RaA). The long-suspected (*180*) β-disintegration mode of RaA has been the subject of considerable study. The first report of the discovery of β-particles by Minder (*116*) was shown to be mistaken (*83, 96*), but since then Karlik and Bernert (*84, 86*) have established the existence of an α-active daughter product (astatine-218), the growth to equilibrium of which has been followed. The α/β branching ratio deduced from these observations is $10^4/3.3$. If the β-transition is allowed, the β-disintegration energy of RaA may be expected to be about 0.3 Mev (*50, 57, 86*). This value would satisfy the requirements of the balance of energy in the branching process.

Astatine-218 (At^{218}). The (extrapolated) air range of the α-particles has been given as 5.53 cm, and the energy of the particles as 6.63 Mev (disintegration energy 6.75 Mev), by Karlik and Bernert (*86*). From their rate-of-growth studies, these authors estimate the half-life as a few seconds. These observations have been confirmed by Walen (*184*) and, further, evidence has been adduced for the β/α branching of At^{218} itself to the extent of about 10^{-3}:1. Confirmation of this conclusion must be awaited, since Walen gives 1.3 sec as the half-life of the daughter product Rn^{218}, whereas Studier and Hyde (*162*) report the artificial production of this species with half-life about 0.02 sec.

Radium B (RaB). There is still no certainty regarding the details of the β-γ disintegration of RaB based upon coincidence studies. Constantinov and Latyshev (*29*) redetermined the effective β-particle endpoint energy as 0.72 Mev, and Feather and Richardson (*55*) put forward new arguments to show that the energy of one of the prominent γ-rays should be added to give the total disintegration energy. Siegbahn (*154*) has remapped the natural β-particle (line) spectrum and recalculated the energies of the principal γ-rays as 52.83, 241.0, 257.8, 294.2 and 350.9 kev, respectively. These determinations were based on absolute measurements of $H\rho$ for the more intense photoelectron lines using semicircular focusing. Earlier in the period under review similar absolute measurements were made by Harper and Roberts (*73*). For the *H*-line Harper and Roberts obtained 1931.9 gauss-cm; Siegbahn obtained 1927.8 gauss-cm. These values are to be compared with earlier standardizations of 1925.5 (Ellis, 1934) (*41*) and 1931.8 (Scott, 1934) (*150*). The intensity of the 52.8 kev γ-ray in emission was determined by Tsien (*174*) as 1.6 $\pm$ 0.8 per 100 disintegrations.

Radium C (RaC). Constantinov and Latyshev (*29*) determined the maximum energy of the complex β-spectrum as 3.173 ± 0.020 Mev and estimated the intensity of the partial spectrum having this endpoint energy as 0.23. Feather and Richardson (*55*) concluded that this partial spectrum belongs to a transition in which the residual nucleus is left with 0.606 Mev energy of excitation and, on this basis, suggested that the other main partial spectra have maximum energies of 1.51 ± 0.02 Mev and 0.80 Mev, and intensities 0.4 ± 0.1 and roughly 0.2, respectively. A detailed reinvestigation of the complicated γ-ray spectrum was made by Russian workers and summarized by Latyshev (*98*). Complete analysis of this β-γ disintegration will challenge experimenters for many years more.

As regards the rare α-mode of disintegration, Chang (*24*) obtained a three-line spectrum using semicircular focusing and gave energies and intensities as $(5.517, 5.466, 5.333) \pm 0.02$ Mev and $(1.6, 2.0, 0.7) \times 10^{-4}$, respectively. These are to be compared with the accepted (*146*) two-line values of 5.507, 5.446 Mev and $(0.94, 1.13) \times 10^{-4}$, respectively.

Radium C′ (RaC′). No essentially new information concerning this pure α-active body has been obtained since 1939. The half-life, first determined by a coincidence method by Dunworth (*38*), was re-evaluated by many workers employing different variants of the same technique. Thus Rotblat (*142*) obtained $(1.45 \pm 0.05) \times 10^{-4}$ sec, Ward (*186*) $(1.48 \pm 0.06) \times 10^{-4}$ sec, Jacobsen and Sigurgiersson (*79*) $(1.55 \pm 0.05) \times 10^{-4}$ sec, Rowlands (*143*) $(1.40 \pm 0.15) \times 10^{-4}$ sec and Bunyan, Lundby, Ward and Walker (*18*) $(1.47 \pm 0.07) \times 10^{-4}$ sec. As concerns the α-radiation, the energy of the most intense long-range group was redetermined by semicircular focusing by Chang (*24*) as 9.08 ± 0.02 Mev. Higher precision had, however, previously been attained by Rutherford, Lewis and Bowden (*144*).

Radium C″ (RaC″). No new information regarding RaC″ has been published since 1940. From earlier results (*37*) it would appear that the maximum energy of the β-particles of the main spectrum is 1.88 ± 0.15 Mev. On this basis it is to be expected that γ-ray energy to the extent of 4.2 ± 0.2 Mev is emitted in almost every disintegration. There is good reason to believe that de-excitation of the residual nucleus is usually a single quantum process (*55*); if this is so, then RaC″ emits γ-rays of considerably higher quantum energy than does any other of the classical radioelements.

Radium D (RaD). Present knowledge concerning the β- and γ-radiations of RaD provides, if anything, a less satisfactory picture of the process than did the knowledge available in 1939. Then it was assumed that a single mode of β-disintegration (maximum β-particle energy not greater than 15 kev) leaves the residual nucleus RaE always in a state of 46.7 kev energy of excitation. On the other hand, the energy of the 46.7 kev γ-ray, observed in emission and through the natural photoelectrons from the L, M and N shells of the residual atom, was at that time the only well-established datum upon which this picture was based. In 1939, however, difficulties concerning intensities began to appear serious (*102*), and the presence of a second γ-radiation (of 42.6 kev energy) was reported (*1*). Now, after a further ten years' work, chiefly by Tsien and his collaborators (*35, 58, 60, 125, 173, 176, 178, 179*), at least 7 γ-rays are assumed to be known, and the statement has even been made that the radiations from RaD include the K X-radiations of bismuth (about 1 quantum per 100 disintegrations). Leaving this last assertion on one side (for it would wreck any understanding of the matter within the framework of present ideas) we may list γ-ray energies and intensities as follows:

Quantum energy (kev)	46.7	42.6	37 ± 0.5	31.3 ± 0.8	23.2 ± 0.6	16.1 ± 0.4	7.3 ± 0.7
Emission intensity (%)	2.8 ± 0.6	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.2	~1	~0	~10

In spite of the apparent complexity of the position, it does not seem impossible to the present reviewer that 5 of these 7 γ-rays (all except those of energy 42.6 and 37 kev) might arise as the result of the unique excitation of the 46.7 kev level. It will be noticed that, within the limits of error stated, $16.1 + 31.3 = 46.7$ and $16.1 + 7.3 + 23.2 = 46.7$. This observation may restore some simplicity to the picture, but more than numerical coincidence will be required before the disintegration is fully understood. In the meantime, it may be stated that de-excitation of the 46.7 kev state by the one-stage process (direct to the ground state) cannot occur in more than about 15% of all disintegrations, and that the intensity of the fluorescent L X-radiation (of bismuth) is consistent with L-shell ionization to the extent of about 0.7 per disintegration. Also, it may be remarked that 7.3 kev is the lowest energy so far recorded for any nuclear γ-radiation, though it is not, of course, established that this radiation is emitted in a transition to the ground state of the RaE nucleus. It appears that the 31 kev component was first observed in emission by Salgueiro (*147*).

Radium E (RaE). The "classical" problem of assimilating detailed information concerning the form of the β-particle energy spectrum with calorimetric determinations of the mean energy of the particles was virtually complete at the beginning of 1940. Two further contributions to this problem only call for comment. Neary (*118*) investigated the form of the energy spectrum and deduced a value of 340 kev for the average kinetic energy of the β-particles, and Zlotowski (*190*) carried out an accurate determination of the heating effect (using sources up to 80 mc in strength in an "adiabatic" microcalorimeter), obtaining 320 ± 5 kev per disintegration [to be compared with the earlier values of 344 ± 34 and 337 ± 20 kev of Ellis and Wooster (*42*) and Meitner and Orthmann (*115*), respectively]. Very recently Neary's energy spectrum was thoroughly confirmed by Langer (*97*).

That RaE, like other radioactive Bi isotopes, undergoes dual disintegration (α/β branching ratio roughly $3:10^7$) was established by Broda and Feather (*17*) (1947) after Feather (*51*) had pointed out that the then accepted assignment of the slow-neutron induced activities of thallium would indicate, if it were correct, a branching ratio more nearly of the order of 1:10. Broda and Feather showed that the accepted assignment was, in fact, incorrect, thallium-206, the product of the α-disintegration of RaE being the 4.2-min body of Fajans and Voigt (*45*).

Radium F (Polonium) (Po). As already mentioned, the α-particles of Po are frequently used for calibration purposes, when energy and range determinations are in question. In this connection, the standard values adopted are: energy 5.2984 ± 0.0021 Mev, air range 3.843 ± 0.006 cm. Faraggi (*46*) determined the concentrated half-tone emulsion range as 21.5 ± 0.2 μ.

Using Po α-particles to test the behavior of a cyclotron magnet operated as a semicircular focusing spectrograph—and to test the method of track counting in photographic emulsions as a means of mapping α-particle spectra—Chang (*22*) (1946) discovered what appeared to be a weak many-lined fine-structure. Further

investigations by Chang (*24*), and more particularly by Wadey (*183*) with a similar experimental arrangement, showed that this apparent fine-structure must have an entirely trivial origin (probably in the penetration of Po into inter-crystalline cracks in the source support), but for two years it was accepted at its face value and at least three independent investigations of the γ-rays were carried out in an attempt to clarify the contradictory situation.

In the first of these investigations de Benedetti and Kerner (*6*) were able to follow the absorption in lead to $5\frac{1}{2}$ cm thickness (reduction by a factor of nearly 200 in γ-ray intensity).

Later Siegbahn and Slätis (*158*) reported measurements to 3 cm thickness. A single component radiation (of about 0.8 Mev quantum energy) only was deduced from these results. By magnetic analysis, using external photoelectrons, Siegbahn and Slätis determined the energy more closely as 0.77 Mev.

The third investigation of the γ-radiation, by Zajac, Broda and Feather (*189*), was concerned chiefly with possible softer components. The intensity of the 0.77 Mev radiation was given as $(1.0 \pm 0.4) \times 10^{-5}$ quanta per disintegration, and a nuclear radiation of 84 ± 4 kev energy and roughly the same (quantum) intensity was also set in evidence (by "critical" absorption measurements). Reasons were given for thinking that these two radiations are emitted in cascade (the softer radiation preceding the harder). If this interpretation is correct, the most intense fine-structure component in the α-particle spectrum would have an energy of 4.47 Mev and an intensity of roughly 10^{-5}. It may be said that to date no fine structure has been definitely observed.

Thallium-206 (RaE″). As noted above, this body is formed in the rare α-mode of disintegration of RaE. It was collected by recoil (from a source of RaE on platinum of initial strength 21 mc) by Broda and Feather (*17*). The maximum energy of the β-particles is 1.70 ± 0.05 Mev and the half-life is 4.23 ± 0.02 min. No γ-radiation has been observed.

Thorium (Th). Several apparently reliable determinations of the standard air range of the Th α-particles were made in the decade 1930–39 without disclosing any real agreement. Now the energy (total ionization) determination of Clark, Spencer Palmer and Woodward (*28*) (3.976 $\pm$ 0.020 Mev) and the C2 emulsion range of Green and Livesey (*67*) (15.0 ± 0.2 μ) give a point lying clearly on the emulsion range-energy curve, so may be taken as mutually confirmatory. In that case the shortest of the previously reported ranges would appear to be correct, and a "best" value of 2.49 ± 0.02 cm may be accepted. Faraggi (*46*) determined the concentrated half-tone emulsion range as 14.2 ± 0.2 μ, a result which gives further support to the above conclusion.

It seems inevitable that someone would have made new estimates of the half-life during recent years by the method of α-particle counting from weighed samples, but this reviewer is unaware of any having been published. In an unpublished survey of the earlier determinations, a best value of $(1.39 \pm 0.05) \times 10^{10}$ years was quoted in 1943 (*49*).

Mesothorium 1 ($MsTh_1$). No new determination of the β-particle energy was published during the period under review, but Feather and Richardson (*55*) concluded on the basis of a general argument that the ground-to-ground state transition $MsTh_1 \rightarrow MsTh_2$ is "unobserved," that is, that the complete radiation spectrum includes a soft γ-ray (or corresponding conversion electrons) of intensity

roughly unity. As concerns possible α/β branching, Feather (*50*) deduced an upper limit of 2.2×10^{-7}:1 for the branching ratio.

Mesothorium 2 ($MsTh_2$). Among the classical radioelements giving highly complex β- and γ-ray spectra, $MsTh_2$ has probably been least fully investigated. No significant new information appears to have been obtained since 1940. Some time previously Guében (*70*) claimed to have discovered a rare α-disintegration mode, but it is probable that the true α/β branching ratio is even somewhat smaller than for $MsTh_1$ (*50*).

Radiothorium (RdTh). The effective energy of the α-particles of RdTh as a single (unresolved) group was deduced from total ionization measurements by Clark, Spencer Palmer and Woodward (*28*) as 5.38 ± 0.02 Mev and the C2 emulsion range determined by Green and Livesey (*67*) as $22.9 \pm 0.2\ \mu$. Very recently Rosenblum, Valadares and Perey (*140*) re-examined the α-particle spectrum using magnetic analysis (semicircular focusing). Two "lines" of intensities 0.72 and 0.28, and energies 5.423 and 5.338 Mev, were observed. The energy difference (corrected for recoil, 86.7 kev) coincides with the energy of one of the γ-rays (86.8 kev) deduced from the natural photoelectron spectrum, but the presence of a second γ-ray (of energy 83.4 kev), represented by photoelectron lines 2.6 times the intensity of the others, is still unexplained.

Results of somewhat less accuracy had previously been given by Chang and Coor (*25*). Taking the energy of the more intense group of α-particles as 5.420 Mev, these authors determined the energy of the other group as 5.354 ± 0.02 Mev, also by the method of semicircular focusing.

Thorium X (ThX). Rosenblum, Valadares and Perey (*140*) made a preliminary study of the α-spectrum of this body by magnetic focusing. They report having obtained the first evidence of fine structure, indications of a group of particles of intensity about 0.25, and energy about 245 kev less than that of the main group (energy 5.681 Mev). In spite of their claim that v. Baeyer, Hahn and Meitner (*3*) (1915) also found indications of a γ-ray of about 250 kev energy, it is certainly true that later opinion (*113*) has been that there is no γ-radiation.

Clark, Spencer Palmer and Woodward (*28*) determined the α-particle energy (for the main group) as 5.66 ± 0.02 Mev, and Green and Livesey (*67*) measured the C2 emulsion range as $24.6 \pm 0.3\ \mu$.

Thoron (Tn). No new results have been published recently (see, however, discussion of rare disintegration modes under ThA on the next page), but Green and Livesey (*67*) determined the C2 emulsion range of α-particles of Tn as $28.7 \pm 0.2\ \mu$.

Thorium A (ThA). The C2 emulsion range of the α-particles is $32.1 \pm 0.3\ \mu$ [Green and Livesey (*67*)] and the half-life 0.158 ± 0.008 sec [Ward (*186*)]. The latter result was deduced from the time distribution of the pulses in a single Geiger counter by the method of the interval selector [see also Roberts (*137*)]. Leigh-Smith and Minder (*103*) postulated the β-disintegration of ThA from the fact that they collected activity from a source of thorium active deposit by light volatilization. They assumed that only an isotope of astatine could be collected in this way. The experiment was carefully repeated by Karlik and Bernert (*86*) with entirely negative results.

Meanwhile, however, the latter authors (*85*) had discovered the presence of α-particles of (extrapolated) air-range 6.84 cm emitted by sources of Tn and ThA in equilibrium, in relative abundance $1.35:10^4$. They assumed the most natural

explanation to be that these α-particles (of energy 7.58 Mev; disintegration energy 7.72 Mev) are emitted by a very short-lived astatine-216 formed from ThA by β-disintegration, 10^4:1.35 being the α/β branching ratio. The difficulties in this explanation were later realized independently by Karlik and Bernert (*86*), Flügge and Krebs (*57*) and Feather (*50*). On the most favorable assumption that the β-disintegration of ThA proceeds by an allowed transition, all three criticisms agreed in showing that there is a deficit of energy of at least 1.2 Mev for the consecutive disintegrations $\mathrm{ThA} \xrightarrow{\beta} \mathrm{At}^{216} \xrightarrow{\alpha} \mathrm{ThC}$, if the α/β branching of ThA takes place as supposed—and always assuming that the disintegration $\mathrm{ThB} \xrightarrow{\beta,\gamma} \mathrm{ThC}$ leaves the ThC nucleus in the ground state. Karlik and Bernert (*86*) concluded that the most likely resolution of the energy difficulty would be to imagine that the last-mentioned assumption is, in fact, incorrect, the known properties of the 60.5-min body of the main thorium series being then regarded as those of a high-energy metastable state of the nucleus ($^{212}_{83}$).

Feather, on the other hand, came to the conclusion that most likely the assumption of α/β branching was itself incorrect, the rare high-energy group prboably being a group of long-range α-particles emitted by ThA. This possibility had been envisaged by Flügge and Krebs and rejected, but Feather showed that it was by no means ruled out if both the excited state of ThA, from which the long-range α-emission occurred, and the ground state had zero spin. So far as the ground state is concerned this is the spin value generally assumed. It should be pointed out that this suggestion implies that there should be a weak "fine-structure" component of energy 5.48 Mev (and intensity at least 1.35×10^{-4}) in the α-energy spectrum of Tn, while the suggestion of Karlik and Bernert implies the presence in a pure sample of ThC of a small proportion of ground-state nuclei to which the half-life of 60.5 min does not apply. Further experiment should thus make possible a test of these alternative hypotheses.

In this connection it might be mentioned that Ghiorso, Meinke and Seaborg (*64*) recently produced protoactinum-228 by deuteron bombardment of thorium and measured the energies of the α-particles emitted by the short-lived products of this body. There can be very little doubt that the group of energy 7.79 Mev is to be assigned to astatine-216. The discrepancy of 0.21 Mev between this determination and that of Karlik and Bernert may already indicate that different groups of particles are in question in the two cases, but it is perhaps too early to press this conclusion.

Thorium B (ThB). The main (F) photelectron group of this body continues to be used in almost all tests of performance, and in all calibrations, of new β-particle spectrographs. The absolute $H\rho$ value for the F-line has been redetermined by Siegbahn (*154*) as 1383.8 gauss-cm. Ellis's (*40*) (1933) value was 1385.8 and that of Arnoult (*2*) (1939) was 1381 $\pm$ 2 gauss-cm. Systematic new work on the radiations of ThB has been reported by Martin and Richardson (*108*) and by Feather, Kyles and Pringle (*54*). The first-mentioned authors determined the form of the primary β-particle spectrum by subtraction (after suitable normalization) of the effect obtained with Th(C + C″) from that recorded with Th(B + C + C″). Using a modification of the Fermi diagram particularly suitable for the analysis of complex spectra, they obtained maximum energies of 330.7 kev and about 570 kev for β-components of intensities 0.88 and 0.12 $\pm$ 0.02, respectively.

Feather, Kyles and Pringle obtained the shape of the partial spectrum of lower energy directly as the momentum spectrum of coincidences between the F-line

photoelectrons and primary β-particles. By Fermi analysis of this spectrum they obtained 355 kev for the endpoint energy. They also observed the higher-energy partial spectrum. Richardson and Martin obtained 0.313 and Feather, Kyles and Pringle obtained 0.288 for the absolute intensity of the *F*-line photoelectron component.

Thorium C (ThC). The C2 emulsion range of the α-particles has been determined as 27.5 $\pm$ 0.3 μ by Green and Livesey (*67*), and Chang and Coor (*25*) have given 6.113 $\pm$ 0.02 Mev and 6.074 $\pm$ 0.02 Mev as the energies of the principal groups in the fine-structure spectrum, determined by track counting on plates exposed in a semicircular focusing spectrograph. These values are some 0.5% higher than those currently accepted, but the accuracy which is claimed is not high. The intensity of the principal photoelectron line (*A*-line) belonging to the 40.8 kev γ-ray of ThC.C'' has been redetermined relatively to that of the *F*-line of ThB.C by Butt (*19*). In agreement with Flammersfeld (*56*), but in disagreement with earlier investigators who obtained much lower values, Butt found that photoelectrons of the *A*-line are emitted in at least 55% of the disintegrations ThC.C''. This observation removes any serious discrepancy which might otherwise have been attached to the determination of the quantum intensity of the 40.8 kev radiation by Kinsey (*89*).

The primary β-particle spectrum corresponding to the disintegration ThC.C' was recently studied in detail by Martin and Richardson (*108*). Apart from knowledge of the γ-rays (*82*, *99*) it would have been very difficult to deduce anything more than that the maximum energy of the main spectrum is 2.2505 $\pm$ 0.0025 Mev, but taking such knowledge into account Martin and Richardson were able to recognize evidence that the combined excitation of the states of ThC' of 1.80 and 1.62 Mev energy is probably about 8% and to set an upper limit of about 6% for the excitation of the state of 0.726 Mev energy. Work by Fultz and Harding (*61*), using a coincidence method, seems to show that 8% is probably somewhat too high.

Thorium C' (ThC'). The C2 emulstion range of the α-particles of the main group has been given (*67*) as 47.5 $\pm$ 0.3 μ. Chang and Coor (*25*) redetermined the energy of the more abundant long-range α-particles as 10.553 $\pm$ 0.01 Mev in full agreement with earlier more accurate determinations. The half-life was deduced from coincidence experiments by Bradt and Scherrer (*13*) ($2.6 \pm 0.4 \times 10^{-7}$ sec), Hill (*76*) ($3.0 \pm 0.15 \times 10^{-7}$ sec), and Van Name (*117*) ($2.2 \pm 0.1 \times 10^{-7}$ sec). It would appear that at least one further accurate determination is necessary.

Thorium C'' (ThC''). Before 1940 the only investigation of the primary β-particles from a pure source of ThC'' in a magnetic spectrograph was that of Henderson (*75*), yielding a value of 1.795 Mev for the endpoint energy. Since then Siegbahn and Johansson (*156*) and Feather, Kyles and Pringle (*54*) have determined the endpoint energy by β-γ coincidence experiments using sources of thorium active deposit, and magnetic analysis. The former authors obtained 1.72 Mev and the latter 1.805 $\pm$ 0.02 Mev for this maximum energy.

About the same time Martin, Richardson and Hsü (*109*) examined the complete β-particle spectrum using a pure source. They deduced a maximum energy of 1.792 $\pm$ 0.007 Mev from a Fermi plot, and discussed the detailed form of the complex continuous spectrum in relation to the level schemes for the residual nucleus Pb^{208} which had been previously proposed. This discussion was carried further by Richardson (*133*), from whose analysis it would appear that in the main the β-particle spectrum is made up of three components of roughly equal

intensity and maximum energies 1.79, 1.51, and 1.28 Mev, respectively. The first of these components corresponds to the excitation of the residual nucleus in the 3.20 Mev state, from which the normal mode of de-excitation is the emission of γ-rays of 0.582 and 2.622 Mev in cascade. The question of the possible rare single-quantum de-excitation of this (3.2 Mev) state has been the subject of much discussion.

Bradt, Halter, Heine and Scherrer (*11*) report that they find "no sign" of the appropriate internal conversion line (and from their curve an upper limit of 1% of the intensity of the K-photoelectron line of the 2.62 Mev γ-ray may obviously be accepted); Martin and Richardson (*108*) set the upper limit at a similar figure. Work by Bell and Elliott (*5*) on the external photoelectron lines puts the relative intensity even lower, not greater than 0.2%. In view of these results the statement of Itoh and Watase (*78*) that the quantum intensity of the 3.2 Mev γ-ray is about 0.03 per disintegration is the more surprising, and even the figure of Stetter and Jentschke (*161*) (0.008 $\pm$ 0.002 per disintegration) would appear to be somewhat excessive.

Uranium-235 (AcU). It is clear that there must have been many opportunities for obtaining complete information concerning the radioactive properties of this body using samples of high purity, but the only reports available for the purpose of this review deal with investigations employing samples of, at the best, medium enrichment.

Using the pulse ionization chamber method of Wytzes and van der Maas (*188*) and samples of normal uranium (0.7% AcU), van der Maas and Yntema (*105*) estimated the air range of the α-particles as 2.83 $\pm$ 0.08 cm. With similar samples, Clark, Spencer Palmer and Woodward (*27*) obtained an energy of 4.396 $\pm$ 0.020 Mev, and deduced an air range of 2.90 $\pm$ 0.03 cm for a group of particles exhibited on their pulse-size histogram as having intensity 0.036 $\pm$ 0.003 with respect to the α-groups belonging to U_I and U_{II} (see above). That this group was due to AcU was confirmed by work with moderately enriched samples, but it was pointed out that the "natural" intensity to be expected for it on the basis of Nier's isotopic analysis (*120*) of leads of different geological age was 0.046 $\pm$ 0.002. The discrepancy appeared entirely outside possible limits of error and the "missing" α-particles were certainly not to be found "hidden" by the α-particles of U_I (as the work with the enriched samples proved).

These authors concluded that the most likely interpretation, on the basis of available evidence, was that the total disintegration energy AcU $\rightarrow$ UY is of the order of 4.8 Mev (rather than 4.47 $\pm$ 0.02 Mev) and that an α-particle group of intensity 0.20 $\pm$ 0.05 and energy 4.75 $\pm$ 0.10 Mev was "hidden" by that belonging to U_{II} in all the analyses which they were able to make. In this connection it might be noted that the U_{II}/U_I α-particle ratio which they obtained with natural samples was just significantly greater than 1 (see above). If this interpretation should prove correct, a fairly intense γ-ray of energy 0.35 $\pm$ 0.10 Mev is indicated.

In the absence of information regarding α-particle counting with chemically determined quantities of AcU, the half-life can merely be quoted, on the basis of Nier's (*119*) results as (7.1 $\pm$ 0.3) $\times$ 10^8 yr.

Uranium Y (UY). This body was studied in a state of almost complete radioactive purity for the first time by Knight and Macklin (*92*). The main disintegration mode was shown to be the emission of a β-particle of maximum energy

210 kev followed by a γ-ray (strongly L-converted) of 35 kev energy. The intensity of the direct ground-to-ground state β-transition was estimated as less than 0.2. The half-life was determined as 25.5 $\pm$ 0.2 hr.

Protoactinium (Pa). The α-particles of Pa were studied by Ringo (*135*), Clark, Spencer Palmer and Woodward (*27*), Tsien, Bachelet and Bouissières (*177*), Ghiorso, Hollander and Perlman (*62*), and Rosenblum and Cotton (*139*). The expected fine structure was discovered independently by Clark and Tsien and their respective collaborators. By the total ionization method, the former workers obtained 5.012 $\pm$ 0.015 and 4.736 $\pm$ 0.020 Mev for the energies of the two groups of particles which they resolved (intensities roughly 0.85 and 0.15). Using a differential ionization chamber and linear amplifier, the latter workers obtained 3.511 $\pm$ 0.010 and about 3.2 cm for the mean air ranges. The two sets of results are concordant, the deduced air ranges given by Clark, Spencer Palmer and Woodward being 3.53 $\pm$ 0.02 and 3.24 $\pm$ 0.03 cm. Similarly, the energy determinations of Ghiorso and collaborators, based upon pulse-size analysis, agree with the other measurements (5.02 $\pm$ 0.01 and 4.72 $\pm$ 0.03 Mev).

The work of Rosenblum and Cotton elaborated this obviously too simple picture of the fine-structure spectrum. In broad features, their magnetic spectrum exhibits the two peaks to be expected on the basis of the earlier work, but Rosenblum and Cotton adopted the preliminary view that the peak of higher energy is composite of six lines (energies 5.042 to 4.880 Mev) and that of lower energy of five lines (energies 4.767 to 4.702 Mev) and that eight other lines are indicated. This would appear to the writer to be going altogether to the other extreme. Evidence from the γ-ray spectrum suggests that the main α-peak may well be double, and the lower-energy peak double or triple, but more work is obviously required before the position is clarified. Haggstrom (*72*) published an account of an incidental investigation of the natural photoelectron spectrum, but without adding to previous knowledge (*112*).

A new determination of the half-life by α-particle counting from a gravimetrically estimated sample has been reported by van Winkle, Larson and Katzin (*187*). These authors give the value (3.43 $\pm$ 0.03) $\times$ 10^4 yr, to be compared with the previously accepted (*69*) (3.2 $\pm$ 0.3) $\times$ 10^4 yr.

Actinium (Ac). Detailed knowledge of the β- and γ-radiations of Ac depends almost entirely upon the recent work of Lecoin, Perey and Tsien. Careful expansion chamber examination of freshly prepared sources by Lecoin and Perey (*100*) led these authors to the conclusion that the maximum energy of the primary β-particles is less than 5 kev. It may be noted that this energy is less than that derived from the "adiabatic" reorganization of the extra-nuclear electrons in the change $Z = 89 \rightarrow Z = 90$. Lecoin, Perey and Tsien (*101*), using a xenon-filled ionization chamber, estimated the emission of a γ-ray of 36.7 $\pm$ 0.7 kev energy, and intensity 0.0025 $\pm$ 0.001, and L X-rays of intensity 0.40 $\pm$ 0.15.

On the basis of these observations, it would appear probable that the β-disintegration is effected by a single mode exciting the 36.7 kev state of RdAc in all cases. It must be admitted, however, that, as observed in the expansion chamber, the intensity of the L-photoelectrons is insufficient to sustain this interpretation. For this reason Frilley, Surugue and Tsien (*59*) directed attention to the alternative assumption that L-shell ionization might be achieved at the expense of the β-transition energy (or possibly electronic reorganization energy alone). This assumption might be helpful if the weak γ-ray could be assigned to the α-mode (see next page).

The rare α-disintegration mode (α/β branching ratio roughly 0.012:1) was thoroughly established by the work of Perey (*126*) in 1939. More recently the energy spectrum of the Ac α-particles has been the subject of investigations by Gregoire and Perey (*68*), Vigneron (*182*), and Ghiorso, Hollander and Perlman (*62*). Gregoire and Perey reported two range groups with air ranges 3.46 $\pm$ 0.02 and 3.1 $\pm$ 0.05 cm (intensities roughly 6:1), but Vigneron and Ghiorso *et al.* are in agreement in concluding that the true spectrum is simple within the limits of resolution and intensity which they could achieve. Vigneron examined the α-tracks in C2 emulsions and deduced an air range of 3.4 $\pm$ 0.1 cm; Ghiorso *et al.*, employing pulse-size analysis, derived an α-particle energy of 4.94 $\pm$ 0.01 Mev. These values are mutually consistent.

Actinium K (AcK). Work by Guillot and Perey (*71*) established conclusively that the direct daughter product of AcK is, in fact, AcX. This was confirmation of the conclusion, which might previously have been assailed on purely logical (as distinct from "general theoretical") grounds, that the production of AcK is by a true α/β branching of Ac. If this is so, then because of the chance of favorable decay periods, it happens that the bulk of the AcX formed from Ac in the first few hours after purification is formed through the chain Ac $\rightarrow$ AcK $\rightarrow$ AcX. Guillot and Perey found five-track "stars" in emulsions rapidly loaded with purified Ac and developed after relatively short exposure, which could have had no other origin.

Nothing new has been published since 1940 concerning the β-radiation or the half-life of AcK, but Lecoin, Perey and Tsien (*101*) examined the γ-radiation in a xenon-filled ionization chamber, and deduced a value of 95 kev for the quantum energy of a radiation fairly heavily absorbed in the *L*-shell. It is probable, therefore, that the main β-transition (of maximum energy 1.1 $\pm$ 0.1 Mev) is to an excited state of the following nucleus (AcX), as it is with Ac (see previous page).

Vigneron (*181*) and Feather (*50, 52*) independently predicted that AcK should itself exhibit α/β branching (ratio, a few per thousand), but no experimental confirmation of the prediction has so far been reported.

Radioactinium (RdAc). The full degree of complexity of the certainly very complex fine-structure spectrum of the α-particles of RdAc is still a matter of some doubt. It would appear that it contains at least 13 discrete lines, possibly more. Tsien (*172, 175*) made measurements of quantum intensity for a few of the low-energy γ-rays and Frilley, Surugue and Tsien (*59*) concluded that the internal conversion of the radiations of 53, 61 and 149 kev energy is abnormally large.

Actinium X (AcX). Nothing essentially new has been reported concerning AcX during the period under review.

Actinon (An). Experiments by Karlik and Bernert (*86*) were interpreted by these authors as indicating the emission of α-particles of about 8-cm range (energy roughly 8.4 Mev), to the extent of 5×10^{-6} per disintegration of actinon, from a source of the emanation in equilibrium with its products. They concluded that these α-particles are emitted by astatine-215 produced in a rare β-mode of disintegration of AcA, though they realize that if their branching ratio be accepted it is necessary to postulate a maximum energy of at least 1.5 Mev for the AcA β-particles and, in consequence, an energy deficit along the main sequence AcA $\rightarrow$ AcB $\rightarrow$ AcC of about 1 Mev. This is an obvious difficulty, and it might be pointed out that Ghiorso, Meinke and Seaborg (*64*) reported that the α-particle energy of "artificially produced" At^{215} is 8.0 Mev, not 8.4 Mev.

Actinium A (AcA). The half-life was redetermined by Ward (*186*) as (1.83 ± 0.04) $\times 10^{-3}$ sec.

Actinium B (AcB). The first satisfactory determination (*148*) of the maximum energy of the β-particles was made just earlier than the period now being considered. Since then only work on the γ-radiation has been reported. Surugue (*163*) put forward a disintegration scheme, and concluded that the residual nucleus (AcC) is formed in the ground state and in states of 404, 487, 764 and 829 kev energy, but that in at least 98% of disintegrations the excitation is either 829 kev (about 20%) or zero (about 78%). Marty (*110*) measured the quantum intensity of the 829 kev γ-ray as 5.4 ± 2.0%.

Actinium C (AcC). No new experimental results have been reported since 1940, but Surugue (*164*) reconsidered the general question of the complex disintegration scheme appropriate to AcC in the light of available information, and Feather and Richardson (*55*) included a point for the rare β-mode of disintegration on a new Sargent diagram, on the assumption that the product nucleus (AcC′) is formed in the ground state with unit probability. On this assumption the point falls clearly on the first forbidden curve. Since the ground-to-ground state transition AcC″ → Pb^{207} is certainly an allowed transition, however, it may well be that the corresponding transition AcC → AcC′ is, in fact, second forbidden and that a soft γ-ray is emitted in almost all these disintegrations.

Actinium C′ (AcC′). Further knowledge concerning the radiations and lifetime of this body await a detailed study of the artificially produced At^{211} of which it is a daughter product (*31*). So far, however, no such study has been reported.

Actinium C″ (AcC″). The only γ-radiation assigned to AcC″ is that of 870 kev energy of which the quantum intensity has been estimated by Surugue (*163*) as about 5×10^{-3}. To a high degree, therefore, the β-particle spectrum is simple and, as already mentioned, is that of an allowed transition. In a reinvestigation of this spectrum by the absorption method, Evans (*43*) determined the maximum energy as 1.445 ± 0.005 Mev, which value is to be compared with the currently accepted value of 1.47 Mev due to Sargent (*148*).

MISCELLANEOUS RESULTS

Reference has been made a number of times in this review to the "artificial" production of one or other of the classical radioelements in controlled transformations; here a summary is given of this aspect of recent research. The species which have been produced artificially are listed, in the order already adopted, with brief information concerning the method of their production.

U_{II}. Produced by the α-decay of Pu^{238}, which was first obtained as the daughter product of the β-decay of Np^{238}, itself produced by the $(d,2n)$ reaction with U^{238} (*153*). Many other methods of obtaining Pu^{238} are now known [for these, and for much similar information relative to this section which is not given here, see Seaborg and Perlman (*152*)]. It will be obvious that since U_{II} can be produced artificially all subsequent members of the uranium-radium series can, in effect, be so produced. In what follows, therefore, independent methods of preparation only will be given.

Io. Produced by the *K*-capture decay of Pa^{230} (*152*), which is itself obtained as one product of the high-energy deuteron- or α-particle bombardment of thorium (*162*).

RaC′. Produced by the α-decay of Em^{218}, itself the product of three successive α-disintegrations starting from U^{230} (*162*). Uranium-230 is one of the products of high-energy α-particle bombardment of thorium.

RaE. Produced by the (d,p) (*30, 77, 104, 168*) and (n,γ) (*152*) reactions with Bi^{209} and by the (α,pn) reaction with Pb^{208} (*171*). Also produced by the α-decay of At^{214}, the fourth α-emitter in the series starting from Pa^{226}, one of the products of the high-energy deuteron bombardment of thorium (*111*).

RaF. Produced by the (d,n) reaction with Bi^{209} (*30, 77, 168*), the $(\alpha,2n)$ reaction with Pb^{208} (*170*) and by the K-capture decay of At^{210}.

RaE″. Produced by the (n,γ) (*130*) and (d,p) (*44, 95*) reactions with Tl^{205} and by the (γ,p)(*4*) reaction with Pb^{207}.

Th. Produced by the α-decay of U^{236}, itself the α-decay product of Pu^{240}, which is formed as one product of the α-particle bombardment of uranium (*80*).

RdTh. Produced by the α-decay of U^{232}, itself the β-decay product of Pa^{232} formed by the $(d,2n)$ reaction with Th^{232} (*65*). Also produced by the K-capture decay of Pa^{228}, a product of high-energy deuteron bombardment of thorium (*64*).

ThX. Produced by the K-capture decay of Ac^{224}, itself the α-decay product of Pa^{228} (see above) (*64*).

Also formed "directly" as one product of the high-energy deuteron (*152*) or α-particle (*123*) bombardment of uranium.

ThC. Produced by the α-decay of At^{216}, the fourth α-emitter in the series starting from Pa^{228} (*64*).

ThC′. Produced by the α-decay of Em^{216}, the fourth α-emitter in the series starting from U^{228}, which is one of the products of the high-energy α-particle bombardment of thorium (*111*).

AcU. Produced by the α-decay of Pu^{239}, which was first obtained as the product of two successive β-disintegrations starting from U^{239} (*151*), formed by the (n,γ) reaction with U^{238} (*114*).

UY. Produced by the $(n,2n)$ reaction with Th^{232} (*121*).

Pa. Produced by the $(d,3n)$ reaction with Th^{232} (*162*), and by the K-capture decay of U^{231} (*124*).

Ac. Produced by the β-decay of Ra^{227}, itself formed by the (n,γ) reaction with Ra^{226} (*127*).

RdAc. Produced by the K-capture decay of Pa^{227}, one of the products of the high-energy deuteron bombardment of thorium (*64*), also directly as one of the products of the high-energy deuteron bombardment of uranium (*152*).

AcX. Produced by the K-capture decay of Ac^{223} (*152*), the α-decay daughter product of Pa^{227} (*64*), also directly as one of the products of the high-energy deuteron- or α-particle bombardment of uranium (*152*).

AcC. Produced by the α-decay of At^{215}, the fourth α-emitter in the series starting from Pa^{227} (*64*).

AcC′. Produced by the K-capture decay of At^{211} (*31*), as already mentioned.

AcC″. Produced by the (n,p) reaction with Pb^{207} (*16*).

In the introduction, reference was made to "secondary effects which occur with active bodies in general." In this category, mention will be made here only of the problem of the appearance of positrons associated with β-decay.

The first observation was that of Chadwick, Blackett and Occhialini (*20*), who used a source of thorium active deposit in an expansion chamber. Positrons were reported to the extent of about 1% of the disintegration electrons. With such a source, this effect may be regarded as a secondary effect associated either with β-emission or with γ-ray emission. But later, similar observations were reported with sources of UX and RaE which emit very little γ-radiation, and with various "pure β-sources" of artificially produced radioelements (*74*). A great deal of work, carried out by many investigators, seemed to indicate that the effect was genuine (*159*), while careful experiments by others were equally convincing in showing that it was not (*10*, *157*).

Positive results were obtained only in experiments using the expansion chamber and, although it cannot be claimed that the effect is thoroughly understood, the most recent report of work by this method (*106*) suggests that the investigators who adopted this approach to the problem were largely misled in their interpretations of track photographs by unrecognized effects of multiple scattering simulating genuine curvature. It would, in fact, appear that there is no obvious anomaly awaiting explanation.

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SCIENCE is no longer accomplished by single individuals. The day is past when one man, working alone in one small room with simple apparatus, can ascertain great fundamental laws of nature. Today, we find not only groups of students and professors working together at a single university, but professors from various universities working together on one particular phase of a problem. Progress is really obtained through action by teams.

—Urner Liddel, at dedication of Harvard Cyclotron, June 15

CURRENT IDEAS ABOUT MESONS

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ONE OF THE most spectacular features of postwar research on the physics of subatomic particles has been the rapid accumulation of information about mesons. These transitory little fugitives from atomic nuclei are still a major enigma of nuclear physics, a fact attested to by the formidable array of super-high-voltage machines now being built for the primary purpose of studying them. Nevertheless, in recent months the major physical properties of two types of mesons have been accurately measured, the existence of at least one more type has been fairly conclusively indicated, and we now have a consistent, even though incomplete, picture of their life history.

This article is primarily concerned with the experimental facts about mesons, but the picture would be incomplete without the purely theoretical ideas. In fact, it is the latter which account for the special interest which nuclear physicists have in mesons. The very existence of such particles was first proposed on theoretical grounds by Yukawa in 1935 in an attempt to explain the force which binds protons and neutrons in nuclei. Despite the failure of his theory and all subsequent similar theories to yield quantitative agreement with experiment, it is generally thought that the basic idea is sound. Although the theories themselves are mathematical and abstruse, the basic concepts are easy to understand. One must not forget, however, the fact that all phenomena in the subatomic realm are very different from those in the macroscopic world of everyday experience, so that any attempt to visualize them by analogy with common things is almost inevitably weird.

We know that neutrons and protons are held together in nuclei approximately 2×10^{-13} cm in radius even though the electrostatic repulsion between two protons at this distance attains the magnitude of six tons. Determining the nature of the force which keeps nuclei from flying apart is the central problem of nuclear physics. We do know its magnitude and its range and that it has the nature of an "exchange force." It was these three properties of the force which Yukawa attempted to explain by his theory.

In considering the last of these three properties first, it is helpful to remember certain other examples of exchange forces. The simplest is that of the hydrogen molecule ion, which consists of two protons and one electron and is held together in a stable configuration by the exchange of the electron. Instead of being permanently attached to either proton, the electron oscillates from one to the other. This interaction keeps the protons close together despite their electrostatic repulsion. It is not possible to explain this occurrence in terms of classical concepts, but the quantum mechanical treatment of the system can be made to give results in quantitative agreement with experiment. The mathematical expressions involved contain terms which it is natural to interpret in terms of this exchange mechanism.

An example which has a much closer analogy with the meson case is the electrostatic repulsion between two elec-

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trons. The experimental facts about this force are completely summed up in Coulomb's law

$$F = k\frac{ee'}{r^2}$$

It has proved useful, however, to go beyond this and to explain the force by the concept of the electrostatic field. We say that each electron is surrounded by an electrostatic field and that these fields interact with each other. We need not use this explanation; in fact, in the beginning, the field concept was a rather artificial one. However, it has become more real as we have gained experience with it and have found other ways, not involving electrons directly, of setting up such fields. Today we seldom stop to realize what a really strange notion it is.

The quantum theory, which now dominates all atomic and nuclear theory, adds still further to the field concept by specifying that it be quantized. The field is described as being made up of virtual photons, and the interaction between two electrons consists of a "virtual exchange" of photons between them. A virtual photon emitted by one electron is absorbed by another. The characteristics of the interaction are related to the properties of photons. The inverse square law is applicable because of the decreasing probability at greater distances of an electron's being "hit" by a virtual photon from another electron. The infinite range of the force is related to the zero rest mass of the photon.

This bizarre little game of electronic ping pong seems highly artificial and not at all satisfying as an "explanation" of the electrostatic force, but this may only be the result of our intuitive unfamiliarity with quantum mechanical concepts. The next generation of physicists may feel quite as comfortable with it as we do with our "field."

The use of the term "virtual" in connection with this interaction requires some explanation. It was discussed in this journal by Primakoff.* An electron can, under certain circumstances (*e.g.*, if decelerated), actually emit a real photon which normally escapes completely from the system rather than being caught by an adjacent electron. In the process, the electron loses energy which is taken up by the photon in accordance with the conservation of energy. In virtual emission, the intermediate state of the system (*i.e.*, two electrons with a photon traveling between them) violates the principle of energy conservation. This is permissible only because the Heisenberg uncertainty principle prohibits us from actually observing the system in this state. The virtual photon emission thus cannot occur unless there is another electron ready to absorb it.

Subatomic Particles

Class	*Name*	*Relative Rest Mass*	*Electric Charge*	*Magnetic Moment*
Nucleons	Proton	1836.6	+e	½
(nuclear constituents)	Neutron	1839.0	0	½
Mesons	π Meson	285	+e, −e	0 or 1
(middle-weight particles)	μ Meson	216	+e, −e	½
Leptons	Electron	1.000	+e, −e	½
(light particles)	Neutrino	0(?)	0	½
	Photon	0	0	0

* H. Primakoff, NUCLEONICS **2**, No. 1, 2 (1948).

This picture is simply an attempt at a verbal expression of the mathematical representation of the force, and it is difficult to know how far one can take it literally.

The analogy between this electron-photon interaction and the nucleon-meson interaction is very close, the differences between electrostatic and nuclear forces coming from the differences between photons and mesons. Consider first the force between a neutron and a proton. We may say that the proton is surrounded by a positive meson field. This is another way of saying that the proton exists most of the time as a proton but part of the time as a combination of a neutron and a meson, which in this case must be a positive meson in order to conserve charge. When the proton is dissociated, its meson may be captured by a neighboring neutron, which thus becomes a proton, leaving the original proton as a neutron. We can represent the process by the equation

$$p_1 + n_2 \rightarrow n_1 + \mu^+ + n_2 \rightarrow n_1 + p_2$$

in which μ^+ is a positive meson. The net result of the process is that a neutron and a proton have changed places, not by actually moving but by exchanging the only property that distinguishes them, their charge.

One can equally well explain the neutron-proton force by postulating a negative meson field for the neutron. Incidentally, this negative meson cloud may explain why the neutron has a magnetic moment like that of a spinning negative particle. The interaction process in this case is

$$n_1 + p_2 \rightarrow p_1 + \mu^- + p_2 \rightarrow p_1 + n_2$$

Similarly the existence of proton-proton and neutron-neutron forces compels one to postulate the existence of uncharged mesons and the interactions

$$p_1 + p_2 \rightarrow (p_1 + \mu^0) + p_2 \rightarrow p_1 + (\mu^0 + p_2) \rightarrow p_1 + p_2$$

$$n_1 + n_2 \rightarrow (n_1 + \mu^0) + n_2 \rightarrow n_1 + (\mu^0 + n_2) \rightarrow n_1 + n_2$$

The mass of the meson follows from this picture by a very simple calculation. Since the dissociation of a proton into a neutron and a meson is forbidden by the law of conservation of mass-energy, it can occur only because of the uncertainty principle, according to which variations in energy ΔE can exist only for a very short time Δt where $\Delta E \cdot \Delta t \leq \hbar$ ($\hbar$ is Planck's quantum constant). If the meson travels with its maximum possible velocity c after being emitted, the farthest it can get in the time Δt is $c\Delta t \leq c\hbar/\Delta E$. Writing this in terms of the meson mass μ by the Einstein relation $\Delta E = \mu c^2$, we have $c\Delta t \leq \hbar/\mu c$. If a neutron and a proton are separated by more than this distance, they cannot interact by exchanging mesons because the virtual meson cannot travel from one to the other in the time that it exists. Thus we have

$$\text{Range of nuclear force} = \frac{\hbar}{\mu c} \approx \frac{4 \times 10^{-11}}{\mu}$$

where μ is measured in terms of the mass of the electron. The range of the force is known to be approximately 2×10^{-13} cm, from which we obtain as the meson mass the value 200 times the electron mass. There are considerable uncertainties in this calculation, but it does fit the experimental facts as to order of magnitude and predicts a meson mass intermediate between that of the electron and the nucleon.

In 1937, two years after Yukawa advanced these ideas, particles were observed in cosmic radiation which seemed to fit his description. Neddermeyer and Anderson at the California Institute of Technology were studying the mechanism of energy loss of cosmic-ray particles. In quantitative agreement with theoretical predictions, they found that electrons lose energy by the production of a whole shower of electrons through a kind of chain reaction. But they also found particles which

gave tracks in a cloud chamber which looked like electron tracks but which lost energy apparently only by ionization of the gas atoms. They could not be protons because their tracks were not dense enough. Almost simultaneously Street and Stevenson at Harvard University, measuring momenta of cosmic-ray particles by observing their curvature in a magnetic field in a cloud chamber, discovered that some particles of fairly low momentum could penetrate much greater thicknesses of lead than would be possible for either protons or electrons of this momentum. The hypothesis that they were a hitherto unknown species of particle with intermediate mass found quick acceptance.

In the three years from their discovery to the curtailment of cosmic-ray research by the war, data on mesons accumulated slowly. Only two methods of research were available—cloud-chamber studies, in which range, momentum, and ionization were measured, and absorption measurements, in which counters in various combinations with absorbers of various materials were used. It was found that the meson has a short lifetime (about 3 microseconds), as expected, but it did not appear to produce an electron when it vanished, as theory predicted it should. The mass was found to be in the neighborhood of 200 electron masses, but it could not be stated with certainty that the mass was unique. It was found that twelve times as many mesons existed on Pikes Peak as at sea level and that each Pikes Peak meson was ten times as likely to disintegrate a nucleus in a lead plate as was a sea-level meson. As one of three possible explanations of this effect, Neddermeyer and Anderson suggested that mesons might have a larger average mass at high altitudes. This turned out much later to be correct, as we shall see.

With the termination of the war, cosmic-ray research took up again where it had left off. At first the data seemed merely to substantiate and intensify a basic inconsistency that had been discernible before the war. It seemed that the interaction of mesons with nucleons (*i.e.*, protons and neutrons) was very strong in some cases and very weak in others. The primary cosmic rays entering the atmosphere from outer space appeared to be predominantly protons, and they were nearly all absorbed in the top ten percent of the atmosphere, knocking mesons out of nuclei. This indicated very strong interaction. Yet the mesons then penetrated through the remaining ninety percent of the atmosphere and even far beneath the earth, almost oblivious of the nuclei therein. This almost complete lack of interaction was very mystifying, since theory strongly indicated that processes induced by mesons should be equally as probable as those in which mesons are created. Among the hypotheses suggested to resolve the difficulty was that of Marshak at the University of Rochester, who assumed two different kinds of mesons. The first, having strong interaction with nuclei, was created by the primary protons. It decayed after a short time into a lighter meson having weak interaction and hence great penetrating power. This hypothesis was quickly and dramatically confirmed.

There were, in the postwar situation, three important new factors bearing on cosmic-ray research. First, C. F. Powell of the University of Bristol, England, had been working with Ilford, Ltd., a British photographic firm, to develop photographic emulsions specially adapted to record tracks of charged particles. Plates were made which would show tracks of slow protons or alpha particles but were not sensitive to the so-called "minimum ionization," *i.e.*, the amount of ionization produced by a very high energy proton or by an

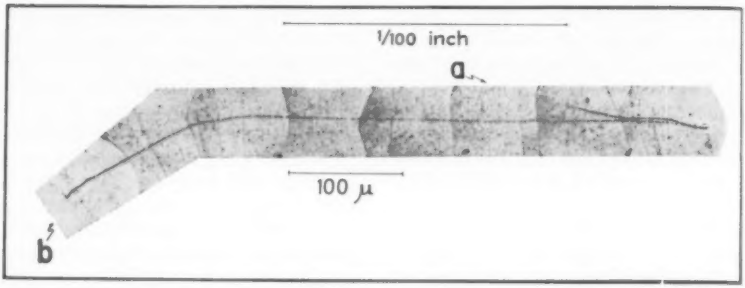

FIG. 1. π-μ decay. A π meson enters the emulsion from direction *a*, comes to the end of its range, and emits a μ meson which travels 610 microns before stopping

electron at any energy. These plates were put to work on mountain tops recording cosmic-ray tracks. Second, under the sponsorship of the Office of Naval Research, high altitudes were much more readily accessible than they had previously been—up to 40,000 feet in B-29 airplanes and up to more than 100,000 feet in special helium-filled balloons. Third, the first of the new multi-million-volt accelerators, the University of California's synchrocyclotron, began to operate. In March, 1948, it was announced by Gardner and Lattes that mesons were produced by alpha-particle bombardment of nuclei in this machine.

The first real break in the meson mystery came a year before this, however. In May, 1947, Lattes, Muirhead, Occhialini, and Powell announced in cautious, but convincing, language the discovery of two distinct kinds of mesons differing in mass. Studying with a microscope the photographic plates which had been kept on a mountain top for a few days, these investigators found many tracks which could be identified as mesons and very rarely a circumstance like that shown in Fig. 1. By measurements of the number of exposed silver grains per unit length of track and of the crookedness of the tracks, it was possible to determine the direction of motion of the particles and to make estimates of their masses. Thus it was possible with fair certainty to interpret the phenomenon of Fig. 1 as resulting from a heavy meson entering the emulsion and decaying into a lighter one, the ratio of their masses being somewhere in the range 1.3 to 1.8. Estimates of the lower limit of the lifetimes of the mesons and several other properties could also be made.

The various kinds of meson tracks observed were classified phenomenologically by Powell and his associates according to what was observed at the ends of the tracks. This nomenclature has become standard, but it is unfortunately somewhat confusing because the number of different kinds of mesons turned out to be less than the number of categories chosen, so that identical mesons are sometimes called by different names.

ρ meson—The rho meson is simply one which is observed to stop in the emulsion without producing any observable product. Since its destiny is anybody's guess, we may for mnemonic purposes call it the "riddle meson" (rho for riddle). It is seldom encountered in current meson literature.

σ meson—Sigma (for "star producing") denotes a meson which causes a nuclear disintegration at the end of its track, the charged fragments being

observed as prongs of a "star," such as shown in Fig. 2. Less than ten percent of mesons stopping in the emulsion were found to be σ mesons.

π meson—The pi (for "primary") meson is distinguished by the fact that it decays into the less massive secondary mu meson.

μ meson—The mu meson, distinguished by having come from a pi, can be remembered by the word "mundane," since it is the meson that is observed at the surface of the earth or below it.

The discovery of the British group and other more recent ones, many of which also utilized the photographic plate technique, have during the past year yielded a fairly complete and consistent picture. The ability to manufacture mesons at will in the new accelerators (several of which will have produced mesons by the time this is published) and hence to deflect them in magnetic fields and subject them to other inconveniences has made possible more accurate quantitative data. The rest of this article will outline the current ideas without attempting in most instances either to identify the source of the information or to distinguish between well-attested facts and slightly shaky inferences. Some of the ideas will doubtlessly prove to be wrong, but the main features are almost surely correct.

Two kinds of ρ mesons, distinguished by positive and negative electric charge, are observed in approximately equal numbers in cosmic rays. Since it is defined by the absence of any observable property, the ρ meson is not a unique particle. It may sometimes be a π meson which happens to knock only neutrons out of a nucleus so that the star is not visible, or it may be a μ meson. It will be remembered that Powell's original plates were not sensitive to electrons, so that he classified all μ mesons which were born outside the emulsion as ρ mesons. The Kodak Research Laboratory has recently developed electron-sensitive plates.

Most, if not all, σ mesons are negatively charged π mesons, although a few could be negative μ mesons or possibly positive π mesons.

π mesons must be subdivided into positive π^+ and negative π^- and probably also neutral π^0, although no conclusive evidence for the latter has been found. Their mass is 285 ± 5 times the electron mass. They can be produced by collisions between nucleons if the kinetic energy is in excess of about 150 Mev, since by Einstein's mass-energy relation, 285 electron masses equals 146 Mev. In meson production by alpha-particle bombardment, approximately one π^+ is knocked out for every four π^- when the target is carbon, but in heavy elements π^- are produced almost exclusively. This is reasonable, since the π^+ have to escape through a potential barrier (the one which keeps protons in the nucleus) that is higher in heavy nuclei, while π^- experience no such impediment.

The π^+ is always produced at high energy because of the electrostatic repulsion between it and the protons in the nucleus, and hence in the ordinary photographic plates (which are sensitive only to low-energy mesons)

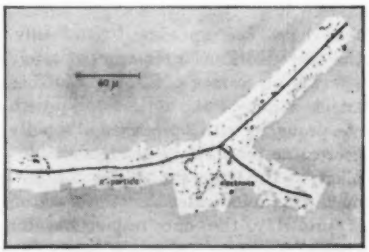

FIG. 2. Nuclear star. A π^- enters from the left and disintegrates a nucleus in the emulsion, producing two heavy fragments (dense straight tracks) and two electrons (faint crooked tracks). The incident particle could also be correctly called a σ meson

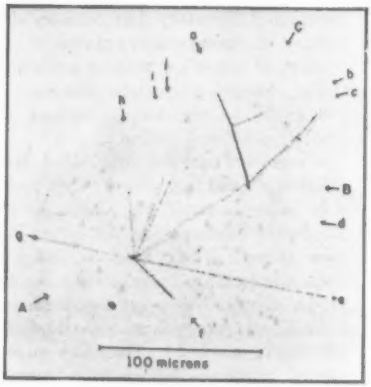

FIG. 3. Meson production and capture. A nuclear explosion at *A* produced by an unobserved high-energy particle (probably a neutron) releases nine charged particles. One of these is identifiable as a π^- by the fact that it stops at *B* and produces another disintegration releasing three visible particles. One of these (labeled *a*) is a heavy fragment which in turn disintegrates at *C*

its birth cannot be observed. π^- can be produced at sufficiently low energy to be visible as one prong of a star. An example is shown in Fig. 3.

A π^- encountering a nucleus can disintegrate it and form a star. These meson-induced stars tend to be smaller, that is, to have fewer prongs, than the previously mentioned nucleon-induced stars. With the low-energy mesons that have been produced artificially, the star distribution is approximately ¼ with no prongs (*i.e.*, only neutrons knocked out of the nucleus), ¼ with one prong, ¼ with 2 prongs, and rapidly decreasing proportions of higher multiplicity. Its large probability of producing stars indicates that the π meson is probably the one responsible for nuclear forces by Yukawa's theory.

If a π^- does not encounter a nucleus, it decays into a μ^- and a neutrino.

$$\pi \rightarrow \mu + \nu$$

The half-life for this decay is $(8 \pm 2) \times 10^{-9}$ second. A π^+ also decays into a μ^+ and a neutrino with a lifetime which is presumably similar. Whether a π^+ ever disintegrates a nucleus is not known, although the probability at least at low energy is certainly small because of the electrostatic repulsion.

μ mesons are apparently produced only by decay of π mesons. The apparent impossibility of knocking them out of nuclei is one argument in favor of the present belief that μ mesons are not connected with nuclear forces, as had originally been supposed. The mass of μ^+ is 216 $\pm$ 5 times the electron mass, and that of μ^- is probably identical. Since only two particles result from the π decay, conservation of momentum and of energy dictate that all μ mesons have the same energy in the coordinate system in which the decaying particle is at rest. Since π mesons can decay at high velocity, μ mesons of high energy are found in cosmic rays. In the usual photographic emulsions, π-μ decays are observed only at very low energy, so that the length of μ tracks is always very close to 600 microns, corresponding to 4.1 Mev.

The theoretical calculation of this energy is a simple and interesting problem in relativistic dynamics. Since we assume that the π meson is at rest and has no kinetic energy, the only energy available for the reaction is that contained in its mass πc^2. (We shall for the moment use π and μ to denote the masses of the respective mesons.) This must be balanced against the sum of the kinetic energies E and the mass energies (zero for the neutrino) of the resulting particles. For conservation of energy,

$$\pi c^2 = E_\mu + E_\nu + \mu c^2$$

The momenta of the μ meson and the neutrino will be equal and in opposite directions. To express this fact in convenient form we shall require the relativistic relation between momentum p, mass M, and kinetic energy E.

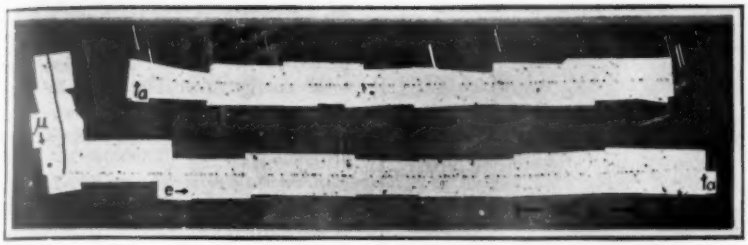

FIG. 4. μ meson decay. The new Kodak emulsion records a μ meson and its decay electron. The electron track is shown in two parts, which should join at *a*

$$p = \sqrt{2ME + E^2/c^2}$$

This simplifies in the neutrino case to

$$p_\nu = E_\nu/c$$

For conservation of momentum, the second required relation is then

$$E_\nu/c = \sqrt{2\mu E_\mu + E_\mu^2/c^2}$$

We can now eliminate E_ν between the two conservation expressions and solve for E_μ.

$$E_\mu = \frac{(\pi - \mu)^2 c^2}{2\pi}$$

The answer in Mev is most easily obtained by introducing the mass m of the electron and remembering that its value is $mc^2 = 0.511$ Mev. A little juggling gives the form

$$\frac{E_\mu}{mc^2} = \frac{\left(\frac{\pi}{\mu} - 1\right)^2}{2\frac{\pi}{\mu}} \cdot \frac{\mu}{m}$$

which shows that the energy is determined primarily by the ratio of the masses of the two mesons, which fortunately is known to be $1.32 \pm .01$, the accuracy being considerably better than that obtainable to date on either mass separately. Using this value and taking $\mu = 216$, one calculates the energy to be 4.3 Mev, which would seem to indicate that the true μ mass is slightly less than 216. This also seems likely from other data. Because of its small mass, the neutrino carries off considerably more energy—31 Mev, according to this calculation.

If it does not approach too near a nucleus, the μ meson in its turn also decays, the half-life being 2.15×10^{-6} second. The evidence now indicates fairly conclusively that the products of the disintegration are two neutrinos and an electron which is either positively or negatively charged, according to the charge of the meson. (See Fig. 4.)

$$\mu^+ \rightarrow e^+ + \nu + \nu$$
$$\mu^- \rightarrow e^- + \nu + \nu$$

The neutrinos are, of course, not observed, and their presence is inferred from the fact that the decay electrons observed in cloud chambers appear to have a uniform distribution in energy up to a maximum at about 55 Mev. If only a single neutrino were emitted, the electron would have a fixed energy.

The calculation of the maximum energy of the decay electron is essentially the same problem that we solved for the case of π decay. The electron will receive the most energy when the two neutrinos both go off in the same direction, and if we substitute the two neutrinos for the one neutrino and the electron for the μ meson, we get the answer in the same form as before. The expression is

$$E_e = \frac{(\mu - m)^2 c^2}{2\mu} \approx \frac{\mu c^2}{2}$$

In the approximation the electron mass is neglected since the meson mass is not even known to an accuracy equal to

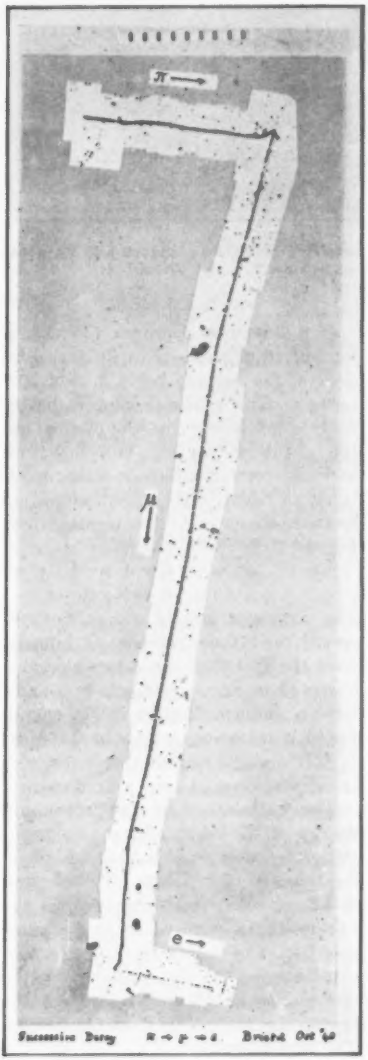

FIG. 5. Successive decay. A π meson entering from the top left decays into a μ with its characteristic 600-micron range, which in turn decays with the release of an electron

one electron mass, and the result is then that the maximum kinetic energy imparted to the electron is just half the total energy available. Usually the electron gets less energy than this, leaving a larger share to the two lighter neutrinos.

Since the electric charge of μ^+ effectively keeps it at a distance from any nuclei, this decay process is probably the fate of all of them. The μ^-, on the other hand, is attracted to nuclei and may be captured by them. Up to a point, this capture process is identical with the capture of a stray electron by an ionized atom. Approaching the nucleus, the meson falls into one of the Bohr orbits, circles the nucleus a few times (perhaps about a trillion), and then drops down to a lower-energy orbit, emitting a gamma-ray photon to take off the excess energy. Continuing these jumps, it soon finds itself in the lowest orbit, but here the similarity to the electron case ceases. The formula derived by Bohr for the radius of the smallest orbit is

$$a_0 = \frac{\hbar^2}{mZe^2}$$

which indicates that the radius is inversely proportional both to the nuclear charge Z and to the mass m of the particle moving in the orbit. If we take lead as a typical heavy element, the value of a_0 for an electron is calculated to be 6.5×10^{-11} cm, while for the μ meson, 216 times heavier, it is only 2.4×10^{-13} cm. This is comparable to the radius of the lead nucleus itself, and it has been calculated that a μ meson in the lowest orbit would actually be inside the lead nucleus about 55 percent of the time. It has been pointed out several times that the μ meson has a very small interaction with nuclei, which means in the present case that it finds the nucleus to be very transparent and can go right through it perhaps 20 trillion times, on the average, without knowing it is

there, but eventually it must collide with one of the protons and be absorbed, probably giving rise to the reaction

$$p^+ + \mu^- \rightarrow n^0 + \nu^0$$

This nuclear capture process is in competition with the decay process so that in matter composed of heavy nuclei the average lifetime of a μ^- is considerably less than a microsecond, while in elements like helium or lithium, capture is so rare that the lifetimes of μ^- and μ^+ are virtually identical.

From another fundamental relation of the Bohr atomic theory, we can get the energy of the meson in its lowest orbit.

$$E = \frac{mZ^2e^4}{2\hbar^2}$$

For a lead nucleus ($Z = 82$), this value is almost 20 Mev. Adding to this the μ meson's 110 Mev mass-energy, it can be seen that a sizeable amount of energy is added to a nucleus when it captures the meson. What happens to this excess energy, which is quite sufficient to blow the nucleus apart, is not at all clear. If the reaction written above, in which a proton is transformed into a neutron and a neutrino, is the correct one, then probably the great majority of the energy is carried away by the unobserved neutrino (since it is so much lighter than the neutron) and the nucleus is left only slightly excited so that it is able only to emit one or a small number of neutrons or in rare cases one or a small number of protons.

With the recently developed electron-sensitive emulsions, it is possible occasionally to observe the successive transformations from π to μ to electron. An excellent example is shown in Fig. 5. Figures 2, 4, and 6 were also obtained with these new emulsions.

Although only the π and μ mesons have been accepted as well-attested members of the family of nuclear particles, there are probably others. Physicists in Britain, France, and America have obtained evidence for a meson

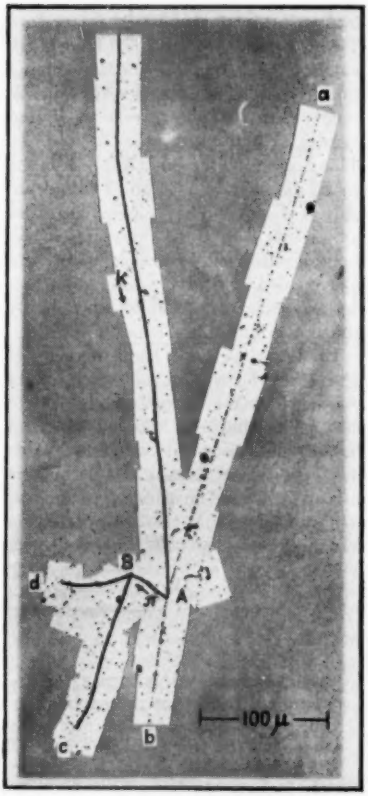

FIG. 6. Evidence for a heavy meson. A κ meson enters at the top and disintegrates at A, releasing two fast mesons (a and b) and a slow π^- which is captured by a nucleus at B with the emission of heavy particles (c and d)

(or mesons) of mass in the range 700 to 1,100 times the electron mass.

A very interesting picture (see Fig. 6) has just recently been published* by the group under Powell at Bristol. It shows what is apparently a meson of mass approximately 1,100 which comes to the end of its range at A and dis-

* R. Brown, U. Camerini, P. H. Fowler, H. Muirhead, C. F. Powell, D. M. Ritson, *Nature* **163**, 47 and 82 (1949).

integrates into three lighter mesons. Two of these (*a* and *b*) have high velocity (hence make sparse tracks) and could be either π or μ, but the third is clearly a π^- which travels to *B* and causes a 2-pronged star (*c* and *d*). This mass-1100 meson is dubbed kappa by its discoverers, who guess that probably it is a κ^+. They suggest also that a picture obtained previously by Leprince-Ringuet in France, showing a heavy meson disintegrating a nucleus and knocking a π^- out of it, probably shows the fate of a κ^-.

Bradt and Peters of the University of Rochester have obtained pictures of mesons of mass approximately 700 to 800 which they call tau. These stop in the emulsion without any observable decay particles, but as the less sensitive plates were used in these experiments, it may well be that the decay products had high velocity and were not seen. In the interest of simplicity, one hopes that τ and κ are the same particle, but only further research will determine this.

A few scraps of evidence seem to point to the existence also of mesons from 3 to 10 times heavier than the electron. These λ mesons (lambda for "light") have been greeted with skepticism because it would seem that they should be produced in copious quantities by cyclotrons running at a few million volts and hence could scarcely have escaped detection so long. Few physicists would at present take a positive stand one way or the other.

* * *

Figures 1 and 3 were supplied by J. J. Lord and Marcel Schein, University of Chicago. Figures 2, 4, 5 and 6 are taken from the articles in Nature *by Brown, Camerini, Fowler, Muirhead, Powell and Ritson, by permission of Prof. Powell.*

TO INCREASE KNOWLEDGE for the sheer delight of knowing and understanding, to further the application of that knowledge in order to ease the burden of existence and strengthen our command over material things; these are the two main features of the twofold aspect of science. Each has its beauty and its poetry, but they are not synonymous. . . . (However) the two aspects of science are interdependent and would soon wither if one tried to separate them. The discoveries of pure science, frequently achieved without any thought of their possible applications, are the indispensable prerequisites of technological advance which, generally speaking, comes quickly in their wake. When the writer of this article established, twenty-five years ago, the first principles of that new branch of physics now known as wave mechanics, he was following primarily a purely intellectual preoccupation, the solution of problems posed by the study of physical phenomena involving quanta, and he was guided by the beauty of new hypotheses whose possibilities he was beginning to discern: no thought of any ultimate application ever entered his head . . . Within a few years these most abstract conceptions of pure science have led to technical applications, and such instances are not rare. Conversely, moreover, technical advances often provide pure science with new fields of study and, by restricting attention to concrete realities, prevent the pure scientist from becoming lost in the clouds.

—*Louis de Broglie,* Research **2,** *101 (1949)*

Introduction to the Theory of Diffusion and Slowing Down of Neutrons—III*

Here the discussion of the age theory is introduced by considering the derivations of both the Boltzmann and age equations. In the preceding portions of this paper on pile theory, the authors discussed the Boltzmann equation in connection with the diffusion theory. Improvements on age theory will be taken up in Part IV, the last paper in this series.

By R. E. MARSHAK,† H. BROOKS,‡ and H. HURWITZ, Jr.‡

Slowing Down of Neutrons by Elastic Scattering§

Derivation of Boltzmann Equation

THE ASSUMPTION has been made in Parts I and II of this paper that all neutrons possess the same energy. This is not true, in general, because even when the scattering of neutrons by nuclei is purely elastic in the sense that no internal degrees of freedom of the nucleus are excited, the neutron may still impart recoil kinetic energy of translation to the nucleus and thus lose an appreciable fraction of its energy. It is the purpose of Parts III and IV of this paper to discuss the solution of the Boltzmann equation when energy losses of this type are present.

The slowing down of neutrons depends upon the scattering cross section which is a function of energy. The unit for cross section measurement is 1 barn $= 10^{-24}$ cm^2, so designated because it represents a large nuclear cross section, that is, "as big as a barn door." Usually the scattering cross section drops off with increasing energy. The case of hydrogen is extreme; the scattering cross section is 20 barns at epithermal energies (*i.e.*, about 1 ev) and falls to less than half this value at 0.5 Mev, finally decreasing to about 1 barn between 5 and 10 Mev. On the other hand, the scattering cross section of carbon falls from about 4.8 barns at epithermal energy to 1 barn at high energies.

We write down the Boltzmann equation governing the distribution of neutrons slowed down by elastic collision with nuclei under the following three conditions:

1. Inelastic scattering can be neglected. This is scattering in which the scattering nucleus is left in an excited state, and which cannot take place until the kinetic energy of the incident neutron, measured in a coordinate system in which the center of mass of neutron plus nucleus is at rest, exceeds the excitation energy of the first excited level of the nucleus. For many moderators, especially light nuclei, the neglect of inelastic scattering is

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* This is the third of a series of four papers compiled from notes taken by H. Brooks and H. Hurwitz, Jr., on lectures given at the General Electric Company by R. E. Marshak during the summer of 1946. A large part of the work described was performed under the auspices of the Atomic Energy Project and thus will be presented in volumes of the National Nuclear Energy Series (Manhattan Project Technical Section).

Parts I and II appeared in NUCLEONICS **4**, No. 5, 10 and No. 6, 43 (1949); Part IV will be published next month.

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§ See paper by R. E. Marshak, *Revs. Mod. Phys.* **19**, 185 (1947) for a more detailed discussion of this subject and for additional references.

a good assumption. For example, the lowest excited level of carbon is 4.7 Mev above the ground level, whereas a negligible number of fission neutrons have kinetic energies exceeding this value. On the other hand, aluminum has a first excited level near 1 Mev, which gives an important contribution to the slowing down of fission neutrons. The first excited levels of heavy elements, such as lead and uranium have, in general, excitation energies that are considerably lower, and so the neglect of inelastic collisions is poor for these elements.

2. The effect of chemical binding is neglected. Naively, one might suppose that this assumption would break down when energy lost in one free collision becomes comparable with the chemical binding energy. This would give:

$$\frac{2}{M} E \gg \hbar\omega \qquad (113)$$

as the criterion of validity of the theory, where E = energy of neutron, M = mass of nucleus, and $\hbar\omega$ = energy associated with one quantum of vibrational energy. For light elements this would imply a breakdown in the theory for a neutron energy of 1 ev, while for heavy elements the breakdown would occur at even higher energies, roughly in proportion to the square root of the mass. In practice, however, the situation is not nearly so serious as this, and a more correct criterion is:

$$E \gg \hbar\omega \qquad (114)$$

that is, the energy itself rather than the change in energy must exceed the energy of a vibrational quantum. Physically, Eq. 114 replaces Eq. 113 because the neutron loses energy in discrete jumps with a few collisions in which n quanta are lost in such a way as to make the average energy loss equal to that in a free collision. The cross section for purely elastic collisions with an isotropically bound particle of mass M is given by:

$$\sigma_0 = \sigma_f \exp\left(-\frac{4E}{M\hbar\omega}\right) \qquad (115)$$

where σ_f is the free-particle cross section. The cross section for energy loss of n quanta, that is, energy $n\hbar\omega$, is given by:

$$\sigma_n = \sigma_f \frac{1}{(n+1)!}\left(\frac{4E}{M\hbar\omega}\right)^n \qquad (116)$$

if $2E/M < \hbar\omega/2$, i.e., the condition of Eq. 113 is *not* fulfilled. The average cross section for energy loss is:

$$\hbar\omega \sum_{n=0}^{\infty} n\sigma_n \cong \frac{2}{M} E\sigma_f \cong \xi\sigma_f E \qquad (117)$$

where $\xi \cong (2/M) \cong$ average logarithmic energy loss, in agreement with free-particle theory. Comparison of Eqs. 115 and 116 shows that the greatest contribution to the total cross section comes from completely elastic scattering, and that this is equal to free-particle total scattering cross section σ_f.

3. The elastic scattering is assumed to be isotropic in a coordinate system in which the center of mass of neutron plus scattering nucleus is at rest. This corresponds to S-wave scattering, and will be true as long as the wavelength of the neutron is large compared with the dimensions of the scattering nucleus. This corresponds to the condition:

$$\frac{\hbar}{MV} = \frac{\hbar}{\sqrt{2ME}} \gg \frac{e^2}{mc^2} A^{1/3} \text{ or}$$

$$E \ll \frac{10Mev}{A^{2/3}} \qquad (118)$$

where A is the atomic weight of the nucleus, M the neutron mass and m the electron mass. Thus, deviations from S-scattering become significant at energies similar to those necessary for the onset of inelastic scattering and are usually unimportant compared to the latter effect. Deviations from S-scattering may occur at a lower energy than that indicated by Eq. 118 because of resonances in the scattering cross section. However, such resonances occur infrequently and when they do, the practical consequences are not very great.

Assuming the foregoing three conditions to be valid, the Boltzmann equation may be written:

$$\frac{\partial N}{\partial t} + \mathbf{v} \cdot \text{grad } N(\mathbf{r},\boldsymbol{\Omega},u,t)$$
$$= -Nv\sigma_T(v) + \int_0^u du' \int d\boldsymbol{\Omega}' N(\mathbf{r},\boldsymbol{\Omega}',u',t) \cdot v'\sigma_s(v') f(\mu_0, u - u') + S(\mathbf{r},u,t) \quad (119)$$

Here, $N(\mathbf{r},\boldsymbol{\Omega},u,t)dr\ du\ d\boldsymbol{\Omega}$ is the number of neutrons in the volume element $d\mathbf{r}$ with velocity vector lying in a solid angle $d\boldsymbol{\Omega}$ about $\boldsymbol{\Omega}$ and with logarithmic energy u within du ($u = \log E_0/E$ where E_0 is some initial energy and E is the energy of interest). The reason for the choice of a logarithmic energy variable will become apparent later. Further, $\sigma_T(v)$ is the total cross section equal to the sum $[\sigma_s(v) + \sigma_c(v)]$ of capture and scattering cross section. The two terms on the left-hand side of Eq. 119 represent the time rate of change of the neutron distribution function moving with the neutron stream in the direction $\boldsymbol{\Omega}$. The first term on the right-hand side of Eq. 119 represents the neutrons removed from the beam by scattering and capture; that is, $N(\mathbf{r},\boldsymbol{\Omega},u,t)v(u)\sigma_T(u)$ represents the number of scattering and capture collisions per unit time at $\mathbf{r}$ and t which occur to neutrons with parameters $\boldsymbol{\Omega}$ and u. The second term on the right-hand side of Eq. 119 represents the neutrons scattered into the beam: $N(\mathbf{r},\boldsymbol{\Omega},u',t)v'\sigma_s(u')$ is the number of collisions per second at $\mathbf{r}$ and t, which occur to neutrons with parameters $\boldsymbol{\Omega}'$ and u' whereas $f(\mu_0,u - u')$ [the function $f(\mu_0,u - u')$ is normalized so that $\int d\boldsymbol{\Omega} \int du' f(\mu_0,u - u') = 1$ for all $\boldsymbol{\Omega}$ and u] is the relative probability of a neutron having the parameters $\boldsymbol{\Omega},u$ after a scattering collision before which their values were $\boldsymbol{\Omega}'$, and u'. The scattering function $f(\mu_0,u - u')$ depends only on $\mu_0 = \boldsymbol{\Omega} \cdot \boldsymbol{\Omega}'$ and the difference between u and u', that is, the ratio of the final to the initial energy. The dependence on the difference $(u - u')$ is the result of the special character of the scattering (S-scattering) while the dependence on μ_0 rather than on $\boldsymbol{\Omega}$ and $\boldsymbol{\Omega}'$ individually follows from symmetry. The explicit form of $f(\mu_0,u)$ is:

$$f(\mu_0,u) = \frac{(M+1)^2}{8\pi M} e^{-u\delta} \left\{ \mu_0 - \left[\frac{(M+1)}{2} e^{-u/2} - \frac{(M-1)}{2} e^{u/2} \right] \right\} \quad (120)$$

A derivation of Eq. 120 is given in Appendix C. The last term on the right-hand side of Eq. 119 is the source term (assumed isotropic) representing the number of neutrons emitted per unit time at $\mathbf{r}$ and t, and with energy corresponding to u.

Equation 119 is the time-dependent Boltzmann equation. Since most problems of practical interest only require a knowledge of the stationary neutron distribution, we can drop the term $\partial N/\partial t$ in Eq. 119. Furthermore, unless it is explicitly stated otherwise, we shall assume that capture is absent, that is, $\sigma_T = \sigma_s = \sigma$.

Derivation of the Age Equation

The stationary Boltzmann equation is:

$$\frac{1}{\sigma} \boldsymbol{\Omega} \cdot \text{grad } \Psi + \Psi(\mathbf{r},\boldsymbol{\Omega},u)$$
$$= \int du' \int d\boldsymbol{\Omega}' \Psi(\mathbf{r},\boldsymbol{\Omega}',u') f(\mu_0,u - u') + S(\mathbf{r},u) \quad (121)$$

In Eq. 121 we have set $\Psi(\mathbf{r},\boldsymbol{\Omega},u) = N(\mathbf{r},\boldsymbol{\Omega},u)v(u)\sigma(u)$. Solutions of Eq. 121 are difficult to obtain for many types of problems, especially for arbitrary variation of σ with energy. For this reason, it is desirable to obtain an

equation which is a good approximation to Eq. 121 but which lends itself more easily to solution. The equation which accomplishes this purpose is the so-called age equation (*4, 5, 24-26**) widely used in slowing-down theory. The age equation can be derived in many ways—from the time-dependent diffusion equation, from simple arguments about the conservation of neutrons, or directly from the Boltzmann Eq. 121. We adopt the last procedure in order to make evident the nature of the restrictions underlying the age approximation.

The first condition on which the age approximation is based is that the distribution function $\Psi(\mathbf{r},\mathbf{\Omega},u)$ is almost isotropic; we retain the first two terms of an expansion in Legendre polynomials, namely:

$$\Psi(\mathbf{r},\mathbf{\Omega},u) = \frac{1}{4\pi}\left[\Psi_0(\mathbf{r},u) + 3\mathbf{\Omega}\Psi_1(\mathbf{r},u)\right] \quad (122)$$

where $\Psi_{0,1}(\mathbf{r},u) = \int d\mathbf{\Omega} P_{0,1}(\mathbf{\Omega})\Psi(\mathbf{r},\mathbf{\Omega},u)$. Substituting this expansion into Eq. 121 and integrating over $d\mathbf{\Omega}$ we obtain:

$$\frac{1}{\sigma}\operatorname{div}\Psi_1 + \Psi_0 = \int_{u-\epsilon}^{u} du'\Psi_0(\mathbf{r},u')f_0(u-u') + S(\mathbf{r},u) \quad (123)$$

where $\epsilon = \log\left(\frac{M+1}{M-1}\right)^2$.

In deriving Eq. 123, we have made use of the general theorem:

$$\int d\mathbf{\Omega} P_l(\mathbf{\Omega}) \int d\mathbf{\Omega}'\Psi(\mathbf{\Omega}',u')f(\mu_0,u-u') = \Psi_l(\mathbf{r},u')f_l(u-u') \quad (124)$$

where

$$f_l(u-u') = \int d\mathbf{\Omega}_0 f(\mu_0,u-u')P_l(\mu_0)$$

The lower limit in the u-integration of Eq. 125 arises from the δ-function occurring in $f(\mu_0,u)$ as seen from Eq. 120 and derived in Appendix C. The integration over $d\mathbf{\Omega}'$ vanishes unless the value of u is such that the argument of the δ-function can be made to vanish for a physically realizable value of μ_0. It is seen that the smallest value of u for which this condition is satisfied occurs for $\mu_0 = -1$, whence

$$\tfrac{1}{2}(M+1)e^{-\frac{u-u'}{2}} - \tfrac{1}{2}(M-1)e^{\frac{u-u'}{2}} = -1$$

or

$$u' = u - \ln\left(\frac{M+1}{M-1}\right)^2 = u - \epsilon \quad (125)$$

which proves the result. Actually, ϵ is the natural logarithm of the largest energy loss which can occur in a single collision, corresponding to a head-on collision in which the neutron bounces straight backward.

We obtain a second equation by multiplying Eq. 121 by $\mathbf{\Omega}$, using Eq. 122 and integrating over $d\mathbf{\Omega}$. This gives:

$$\frac{\operatorname{grad}\Psi_0}{3\sigma} + \Psi_1 = \int_{u-\epsilon}^{u} du'\Psi_1(z,u')f_1(u-u') \quad (126)$$

We now assume that Ψ does not vary much in the logarithmic energy interval between u and $u-\epsilon$. This permits us to introduce the Taylor expansions:

$$\Psi_0(\mathbf{r},u') = \Psi_0(\mathbf{r},u-s) \simeq \Psi_0(\mathbf{r},u) - s\frac{\partial\Psi_0(\mathbf{r},u)}{\partial u}$$

$$\Psi_1(\mathbf{r},u') \simeq \Psi_1(\mathbf{r},u) \quad (127)$$

where $s = u - u'$. If we introduce the approximations in Eq. 127 into Eqs. 123 and 126, we obtain, after changing the variable of integration to s:

$$\frac{\operatorname{div}\Psi_1}{\sigma} + \Psi_0 = \int_0^{\epsilon} ds f_0(s)\left\{\Psi_0(\mathbf{r},u) - s\frac{\partial\Psi_0}{\partial u}\right\} + S(\mathbf{r},u)$$

$$\frac{\operatorname{grad}\Psi_0}{3\sigma} + \Psi_1 = \int_0^{\epsilon} ds f_1(s)\Psi_1(\mathbf{r},u) \quad (128)$$

By making use of Eq. 120 and the

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* *References noted can be found in the complete bibliography published with Part I of this series of papers;* see NUCLEONICS **4**, No. 5, 22 (1949).

definition Eq. 124 we obtain in general:

$$f_l(s) = \frac{(M+1)^2}{4M} e^{-s} P_l \left\{ \frac{1}{2}(M+1) e^{-\frac{1}{2}s} - \frac{1}{2}(M-1) e^{\frac{1}{2}s} \right\} \quad (129)$$

or

$$f_0(s) = \frac{(M+1)^2}{4M} e^{-s}$$

$$f_1(s) = \frac{(M+1)^2}{4M} e^{-s} \left\{ \frac{1}{2}(M+1) e^{-\frac{1}{2}s} - \frac{1}{2}(M-1) e^{\frac{1}{2}s} \right\}$$

Using the results of Eq. 129 and substituting back into Eqs. 128 we obtain the new pair of equations:

$$\frac{\text{div } \Psi_1}{\sigma} + \Psi_0 = \Psi_0 - \xi \frac{\partial \Psi_0}{\partial u} + s(\mathbf{r},u) \quad (130)$$

$$\frac{\text{grad } \Psi_0}{3\sigma} + \Psi_1 = \Psi_1(\cos \textcircled{H})_{av} \quad (131)$$

where

$$\xi = \int_0^s s e^{-s} ds \frac{(M+1)^2}{4M} = 1 - \frac{(M-1)^2}{2M} \ln \frac{M+1}{M-1} \quad (132)$$

$$\int_0^s f_0(s) ds = \frac{(M+1)^2}{4M} \int_0^s e^{-s} ds = 1 \quad (133)$$

$$\int_0^s f_1(s) ds = \int_0^s ds \mu_0(s) f_0(s) = \frac{2}{3M} = (\cos \textcircled{H})_{av} \quad (134)$$

From Eq. 131 we obtain:

$$\Psi_1 = \frac{\text{grad } \Psi_0}{3\sigma[1 - (\cos \textcircled{H})_{av}]} = -\frac{1}{3} \lambda_t \text{ grad } \Psi_0 \quad (135)$$

$$\nabla^2 \Psi_0 = \frac{3\xi}{\lambda \lambda_t} \frac{\partial \Psi_0}{\partial u} - \frac{3}{\lambda \lambda_t} S(\mathbf{r},u)$$

with $\lambda = 1/\sigma$. We now define the age τ such that:

$$\tau = \int_0^u \frac{\lambda \lambda_t}{3\xi} du' \quad (136)$$

For pure elements ξ is independent of energy and may be taken outside the integral in Eq. 136 but in mixtures ξ may vary with energy, so that we retain it under the integral for greater generality. With the definition in Eq. 136, Eq. 135 reduces to:

$$\nabla^2 \Psi_0 = \frac{\partial \Psi_0}{\partial \tau} - \frac{1}{\xi} \bar{S}(\mathbf{r},\tau) \quad (137)$$

where by definition $\bar{S}(\mathbf{r},\tau) = \frac{3\xi}{\lambda \lambda_t} S(\mathbf{r},u)$.

If we let $\xi \Psi_0 = q$, assume ξ is independent of u, and choose $\bar{S}(\mathbf{r},\tau) = Q(\mathbf{r})\delta(\tau)$ (monoenergetic source), we get:

$$\nabla^2 q = \frac{\partial q}{\partial \tau} - Q(\mathbf{r})\delta(\tau) \quad (138)$$

Equation 138 is the required age equation. The quantity q is known as the slowing-down density, and represents the number of neutrons per unit volume per second arriving below the energy E corresponding to age τ.

As an example of the age equation in use, consider an infinite slowing-down medium with an infinite plane source of monoenergetic neutrons. Actually Eq. 138 is the exact analogue of the time dependent heat conduction equation, so that many of its solutions may be obtained in such standard texts as Carslaw's.* However, in order to exhibit the relation of age theory to the more exact treatment, it is convenient to solve Eq. 138 by the method of Laplace transforms. If we take the Laplace transform in Eq. 138 [with $q(\mathbf{r}) = q(z)$, $Q(\mathbf{r}) = \delta(z)$], we obtain:

$$\frac{\partial^2 \phi}{\partial z^2} - \eta \phi = -\delta(z)$$

where $\phi(z,\eta) = \int_0^\infty q(z,\tau) e^{-\eta \tau} d\tau \quad (139)$

This is seen to be the same as the diffusion equation with capture (Eq. 20 in Part I) if we set:

$$L = \frac{1}{\sqrt{\eta}} \quad \text{and} \quad S_0(z) = D\delta(z)$$

Eq. 139 has the solution:

$$\phi = \frac{1}{2\sqrt{\eta}} e^{-|z|\sqrt{\eta}} \quad (140)$$

and reference to a table of Laplace

* H. W. Carslaw, "Mathematical Theory of the Conduction of Heat in Solids" (Dover Publications, New York, 1945)

transforms shows that:

$$\mathcal{L}^{-1}\phi = \frac{e^{-\frac{z^2}{4\tau}}}{\sqrt{4\pi\tau}} = q(z,\tau) \qquad (141)$$

where the symbol $\mathcal{L}^{-1}$ denotes "Laplace Inverse" defined in any standard text on Laplace transformations such as Doetsch's.*

Recapitulation of Assumptions

In the derivation of the age equation (Eq. 138), we added in essence to the usual assumptions of diffusion theory, as stated in Part I, the following additional assumptions:

4. The mean free path does not vary appreciably within any logarithmic energy interval ϵ.

5. The number of collisions experienced by the neutron after leaving the source is large.

6. The distance from the source is not too large.

In accordance with the three conditions of diffusion theory, age theory might be expected to break down close to the source; however, as long as the energy of the neutron is sufficiently degraded, indicating that it has experienced many collisions, the age equation is valid even within distances from the source small compared to a mean free path. This is because the breakdown of diffusion theory, as we have seen, arises from neutrons which have not had time to make collisions after leaving the source, whereas it is exactly these anomalous neutrons which are excluded when we confine our attention to particles of reduced energy. Furthermore a study of the behavior near a plane boundary shows that the proper "extrapolated endpoint," *i.e.*, the distance outside the boundary at which the extrapolated neutron density would vanish, is determined by the mean free path appropriate to the slowest neutrons. Finally, the capture condition does not enter because we have assumed zero capture.

In order to see how the conditions **4, 5,** and **6** were implicit in our derivation of the age equation, we examine more closely the approximations made in solving the Boltzmann equation. For this purpose we use the solution (Eq. 141) of the age equation with the plane δ-source. Now, in the first place, the validity of the expansion in Eq. 122 demands that $\Psi_1 \ll \Psi_0$. But from Eq. 135:

$$\Psi_1 = -\tfrac{1}{3}\lambda_t \operatorname{grad} \Psi_0$$

If we take Ψ_0 from Eq. 141, we have:

$$\frac{+\frac{1}{3}\lambda_t(2z)}{4\tau}\Psi_0 \ll \Psi_0 \qquad \text{or}$$

$$z \ll \frac{6\tau}{\lambda_t} = \left(\frac{6L_s}{\lambda_t}\right) L_s \qquad (142)$$

where $L_s = \sqrt{\tau}$ is the slowing-down length and represents the distance required to slow down a neutron to the energy corresponding to τ. Eq. 142 represents condition **6** above.

In the second place, in assuming the validity of the Taylor expansion (Eq. 127) in the logarithmic energy interval ϵ, we have taken:

$$\epsilon \frac{\partial \Psi_0}{\partial u} \ll \Psi_0$$

But

$$\epsilon \frac{\partial \Psi_0}{\partial u} \sim 2\xi \frac{\partial \Psi_0}{\partial \tau}\frac{d\tau}{du} = \frac{\lambda\lambda_t}{3}\left(\frac{z^2}{2\tau^2} + \frac{1}{\tau}\right)\Psi_0 \qquad (143)$$

This is equivalent to

$$\frac{1}{\tau} + \frac{z^2}{2\tau^2} \ll \frac{3}{\lambda\lambda_t}$$

which requires at least that

$$\tau \gg \frac{\lambda\lambda_t}{3} \qquad (144)$$

This is equivalent to condition **5** above since it states that the slowing-down distance must be large compared with the mean free path for scattering.

Finally, the validity of the second expansion in Eq. 127 requires that the

* G. Doetsch, "Theorie und Anwendung der Laplacetransformation" (Springer, Berlin, 1937).

omitted next term be very small compared with the first term; in other words:

$$\epsilon \frac{\partial \Psi_1}{\partial u} \ll \Psi_1 \qquad (145)$$

Remembering that $\Psi_1 = (\lambda_t/3)(z\Psi_0/2\tau)$ and assuming the condition in Eq. 144 is already well fulfilled, we have:

$$\frac{\partial \Psi_1}{\partial u} \sim \frac{d\lambda_t}{du}\frac{1}{\lambda_t}\Psi_1$$

so that Eq. 145 reduces to:

$$\epsilon \frac{1}{\lambda_t}\frac{d\lambda_t}{du} \ll 1, \quad \text{or} \quad \epsilon \frac{1}{\lambda}\frac{d\lambda}{du} \ll 1 \qquad (146)$$

Equation 146 states that the fractional change in mean free path in the logarithmic energy interval ϵ is small compared with unity, which is condition **4** above.

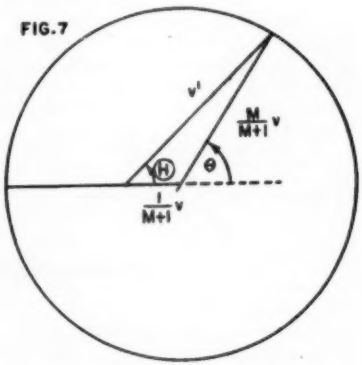
Thus, conditions **4**, **5**, and **6** specify the range of validity of age theory.

APPENDIX C

This appendix is a derivation of Eq. 120 of the text. It is evident that in a coordinate system in which the center of mass of neutron plus nucleus is at rest, the resultant momentum of the particles must be zero, and therefore their individual momenta must be equal in magnitude and oppositely directed both before and after the scattering. Furthermore, since energy is conserved in the collision, it is evident that the velocity of the neutron in this coordinate system is the same before and after scattering.

If v is the initial velocity of the neutron in the laboratory system, then in the center of mass system it has the velocity $[M/(M+1)]v$ while the center of mass itself has the velocity $[1/(M+1)]v$. The situation is illustrated in Fig. 7 where θ is the angle of scattering of the neutron in the center of mass system. The velocity v' after scattering, in the laboratory system, is obtained merely by adding vectorially the velocity of the center of mass to the final velocity of the neutron, obtaining the vector labeled v' in Fig. 7.

FIG. 7



From the figure we obtain immediately:

$$v'^2 = \left(\frac{M}{M+1}v\right)^2 + \left(\frac{1}{M+1}v\right)^2 + \frac{2Mv^2}{(M+1)^2}\cos\theta \qquad (C1)$$

or

$$\frac{E'}{E} = \frac{1 + M^2 + 2M\cos\theta}{(M+1)^2}$$

where E and E' are the initial and final kinetic energies in the laboratory system. If we let

$$E/E' = e^u = (v/v')^2 \qquad (C2)$$

then Eq. C1 may be written:

$$e^{-u} = \frac{1 + M^2 + 2M\cos\theta}{(1+M)^2} \qquad (C3)$$

or

$$\frac{M}{M+1}\cos\theta = -\frac{1}{2}\frac{1+M^2}{1+M} + \frac{1}{2}(M+1)e^{-u} \qquad (C3')$$

Also from the figure we obtain the trigonometric relation:

$$v' \cos \textcircled{H} = \frac{M}{M+1} v \cos \theta + \frac{1}{M+1} v$$

or

$$\cos \textcircled{H} = e^{u/2} \left\{ \frac{M}{M+1} \cos \theta + \frac{1}{M+1} \right\} \tag{C4}$$

Substituting for $\cos \theta$ from Eq. C3′ into C4 leads to:

$$\cos \textcircled{H} = \mu_0 = e^{u/2} \left\{ -\frac{1}{2} \frac{1+M^2}{1+M} + \frac{1}{1+M} + \frac{1}{2}(M+1)e^{-u} \right\}$$

or

$$\mu_0 = \tfrac{1}{2}(M+1)e^{-u/2} - \tfrac{1}{2}(M-1)e^{u/2} \tag{C5}$$

Now, the differential cross section for scattering through the angle θ in the center of mass system is simply

$$d\sigma = \frac{\sigma_s}{2} d(\cos \theta) \tag{C6}$$

on the assumption of isotropy. Because of the relation in Eq. C3, however, Eq. C6 reduces to:

$$-d\sigma = \sigma_s \frac{(1+M)^2}{4M} e^{-u} du \tag{C7}$$

Thus the double integration over angle and energy which occurs in the Boltzmann equation is really a single integral since the angle and energy are related. To retain the double integral symbolism, however, we introduce a δ-function of Eq. C5 to denote the fact that in integrating over $d\Omega'$ we must choose the value μ_0 appropriate to the particular value of u. Thus since $d\Omega_0 = 2\pi d\mu_0$, we have:

$$f(\mu_0, u) = \frac{(1+M)^2}{8\pi M} e^{-u} \delta \left\{ \mu_0 - \frac{1}{2}(M+1)e^{-u/2} + \frac{1}{2}(M-1)^{u/2} \right\} \tag{C9}$$

which was to be demonstrated.

PROGRESS in all science depends largely upon the pooling of knowledge, and its effective coordination. The final success is always the result of a series of smaller successes due to the efforts of many individuals. The wide exchange of scientific information has done more for the advancement of knowledge than any funds awarded for a particular purpose.

—S. A. Goudsmit, Research **2,** *51 (1949)*

Derivation and Integration of the Pile-Kinetic Equations

In calculating the power level of a chain-reacting system as a function of time when certain changes are made in the reactivity it is customary to make use of the so-called "pile-kinetic" equations. These are a set of coupled differential equations involving the power level of the pile and the number of "excited nuclei" whose decay gives rise to delayed neutrons.† We shall describe some methods which can be used to solve the pile-kinetic equations. In particular we shall obtain a general solution for the case where the reactivity does not vary too rapidly with time. We shall also give a careful derivation of the pile-kinetic equations for a general assembly in order to show the assumptions which are implicit in the equations, and the limits of their validity.

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Solution of Equations

The pile-kinetic equations may be written in the form

$$\frac{dn}{dt} = A(t)n + \sum \lambda_i c_i$$
$$\frac{dc_i}{dt} = g_i n - \lambda_i c_i \qquad (1)$$

Here n is the instantaneous rate of fissions in the pile, and the variables c_i are proportional to the number of "excited nuclei" of the ith species which are present in the pile. The constants λ_i are the decay constants which give the rate at which these "excited nuclei" decay and emit delayed neutrons. The constants g_i are related to the fission yields of the different types of delayed neutrons. The variable A is related to the reactivitity of the pile which we assume to be a known function of time. The exact physical significance of the quantities appearing in Eq. 1 will be discussed more carefully in the next section, where these equations are derived.

It will be shown that $A(t) = 1/\tau(k_p - 1)$ where k_p is the prompt multiplication factor and τ is the prompt generation time; c_i is $\epsilon_i m_i/\tau\nu_p$ where m_i is the number of excited nuclei of the ith type which are present in the assembly; and g_i is $\beta_i\epsilon_i/\tau$. In this notation the number of prompt neutrons emitted per fission is ν_p, while the number of excited nuclei of the ith type produced per fission is $\beta_i\nu_p$. The effectiveness of a delayed neutron of the ith type as compared to a prompt neutron is ϵ_i. Since k_p is, in general, less than unity, $A(t)$ is negative.

The nature of the solutions of (1) when $A(t)$ is a constant is well known. The general solution is the sum of solu-

* The Knolls Atomic Power Laboratory is operated by the General Electric Research Laboratory for the Atomic Energy Commission. The work reported here was carried out under contract No. W-31-109 Eng-52.

† F. de Hoffman, B. T. Feld, *Phys. Rev.* **72**, 567 (1947); W. C. Redman, D. Saxon, *Phys. Rev.* **72**, 570 (1947); D. J. Hughes, *et al*, *Phys. Rev.* **73**, 111 (1948).

tions of the form

$$n = n_o e^{pt}$$

$$c_i = \frac{g_i}{\lambda_i + p} e^{pt} \qquad (2)$$

where p is a root of the "inhour" relationship

$$p = A + \sum \frac{g_i \lambda_i}{p + \lambda_i} \qquad (3)$$

Equation 3 has $I + 1$ roots, where I is the number of delayed neutron periods. If the pile is subcritical all the roots will be negative; if it is not, then one of the roots will be positive. After the reactivity has been constant for a sufficient length of time only that term in the solution which corresponds to the largest algebraic value of p will be important; the others (*i.e.*, the transient terms) will have died away. If the assembly is close to critical, the algebraically largest p will be small compared to the λ_i's so that (3) becomes

$$p \sim \frac{A + \Sigma g_i}{1 + \sum \frac{g_i}{\lambda_i}}$$

$$\sim \frac{k_p - 1 + \Sigma \beta_i \epsilon_i}{\tau + \sum \frac{\beta_i \epsilon_i}{\lambda_i}}$$

If the pile reactivity is a step function of time the problem can be solved in terms of the constant reactivity solutions. The amplitude of the transients introduced by the sudden change in reactivity may be obtained simply by making n and c_i continuous at the instant of the jump. Making n continuous amounts to assuming that the reactivity change occurs over a time short compared to the prompt neutron generation time of the pile. A more realistic treatment of the sudden reactivity change would result from the less stringent assumption that the change takes place over a time which is short only compared to the delayed neutron periods. One may then assume that the quantities c_i are constant during the interval of the change. Then Eq. 1 may be integrated, giving the following equation

$$n = n_0 e^{\int_0^t A dt'} \left[1 + C \int_0^t e^{-\int_0^{t'} A(t'') dt''} dt'\right] \qquad (4)$$

$$C = \Sigma c_i \lambda_i$$

where n_0 is the value of n at $t = 0$. Thus, at the end of the interval of reactivity change, n is given by (4) and the c_i's still have their initial value. From this time on, the constant reactivity solutions hold. The amplitudes of the various transients are determined by making n and c_i continuous at this point.

It should be noted that at a time after A has become constant which is large compared to $1/A$, Eq. 4 gives, if $A < 0$,

$$n = \frac{C}{|A|} \qquad (5)$$

Equation 5, in fact, holds quite generally provided that $A < 0$, $\left|\frac{dA}{dt}\right| \ll A^2$ and $\lambda_i \ll |A|$ for all i. The fission rate is therefore proportional to the rate at which delayed neutrons are produced times the prompt multiplication of the assembly.

The assumption that the delayed neutron production rate is constant cannot be used when the change in reactivity occurs over a time interval which is not short compared to the delayed neutron periods. If, however, the change in reactivity is sufficiently gradual, one can obtain a general solution to the problem by making a different approximation. The solution to (1) as given in (2) and (3) is strictly valid only when $A(t)$ is a constant. However, it will be an approximate solution if $A(t)$ is changing gradually. Let us therefore write

$$n = \eta e^{\int_0^t p(t') dt'}$$

$$c_i = (f_i \eta + \epsilon_i) e^{\int_0^t p(t') dt'} \qquad (6)$$

$$f_i = \frac{g_i}{\lambda_i + p}$$

Here $p(t)$ is the algebraically largest root of (3), and is a function of time since A is a function of time. The equations for the variables η and ϵ_i are,

$$\frac{d\eta}{dt} = \sum \lambda_i \epsilon_i \qquad (7a)$$

$$\frac{d\eta f_i}{dt} + \frac{d\epsilon_i}{dt} = -(p + \lambda_i)\epsilon_i \qquad (7b)$$

The main time dependence of the solution is contained in the exponential factor in (6) so that even when tremendous variations in power level occur, the quantities appearing in (7) have comparatively small variations. Equation 7*b* may be interpreted to mean that ϵ_i always tends toward the value

$$-\frac{1}{p + \lambda_i} \cdot \frac{d\eta f_i}{dt}$$

with a "relaxation time" $\frac{1}{p + \lambda_i}$.* Hence, if the reactivity change in a time interval of this magnitude is small, we may assume that ϵ_i is always approximately equal to

$$-\frac{1}{p + \lambda_i} \cdot \frac{d\eta f_i}{dt}$$

Then we obtain from (7)

$$\frac{d\eta}{dt} = -\sum \frac{1}{1 + p/\lambda_i} \frac{d\eta f_i}{dt} \qquad (8)$$

or

$$\frac{d \ln \eta}{dt} = \frac{-\sum \frac{1}{1 + p/\lambda_i} \frac{df_i}{dt}}{1 + \sum \frac{f_i}{1 + p/\lambda_i}} \qquad (9)$$

Using the expression for f_i given in (6) we find

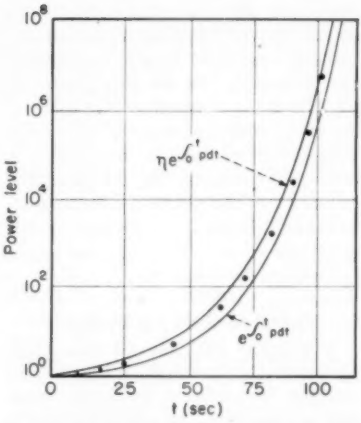
$$\frac{d \ln \eta}{dt} = -\frac{1}{2} \frac{d \ln D}{dt} \qquad (10)$$

$$D = 1 + \sum \frac{g_i/\lambda_i}{(1 + p/\lambda_i)^2}$$

Thus, if $\eta = 1$ and $p = 0$ at $t = 0$,

$$\eta = \sqrt{\frac{1 + \Sigma\, g_i/\lambda_i}{1 + \sum \frac{g_i/\lambda_i}{(1 + p/\lambda_i)^2}}} \qquad (11)$$

* Since p is the algebraically largest root of (3) it follows that $p + \lambda_i$ is always positive. If a different root had been chosen, $p + \lambda_i$ would be negative for at least one i, so that our approximation would not be justified.



Graph showing power level as a function of time for a typical reactor with reactivity increasing at a rate of 5×10^{-5} per sec. The top curve was obtained from Eq. 12. The bottom curve was obtained by omitting the factor η. The points come from an accurate numerical integration of the pile kinetic equations, under the direction of J. Pigott

Our final solution is therefore

$$n = \sqrt{\frac{1 + \Sigma\, g_i/\lambda_i}{1 + \sum \frac{g_i/\lambda_i}{(1 + p/\lambda_i)^2}}}\; e^{\int_0^t p(t')dt'} \qquad (12)$$

This solution holds for arbitrary variation of reactivity with time, provided only that the variation is not too rapid. It is clear that the main variation in n arises from the exponential factor. In a typical case the square root factor changes only by a factor of about three hundred when p goes from zero to infinity.

When the pile reactivity varies in such a manner that the power does not change by a large fraction (*e.g.*, for small sinusoidal variations in reactivity), Eq. 1 may be linearized by writing $n = n_0 + n_1(t)$ and $A(t) = A_0 + A_1(t)$ where n_0 and A_0 are the average values of n and A. Then in the product $A(t)n(t)$ in Eq. 1 the small cross term $A_1(t)n_1(t)$ is neglected. The resulting

equations can then be solved with general $A_1(t)$ by the usual methods for treating coupled linear equations.† By comparing the solution given by Eq. 12 for a sinusoidal variation of reactivity with the results of the "small oscillation" method of treatment, it can be shown that Eq. 12 gives the expansion of the pile response for small frequency correct to terms in the reciprocal of the frequency and independent of the frequency.

Derivation of the Pile Equations

A general assembly of fissionable material can be characterized by a function $P(\mathbf{r},\mathbf{r}'t)$ which is the probability that a neutron liberated in a fission at point $\mathbf{r}'$ and time $t = 0$ gives rise to a fission at point $\mathbf{r}$ and time t, per unit time and volume. For simplicity we shall first assume that the delayed neutron energy spectrum is the same as the fission neutron spectrum so that P is the same for prompt and delayed neutrons. We let $N(\mathbf{r},t)$ be the rate at which fissions are occurring per unit volume at point $\mathbf{r}$ and time t. Each fission process gives rise on the average to ν_p prompt neutrons, and produces $\beta_i\nu_p$ excited nuclei of the ith kind. If the number of such nuclei present per unit volume is $M_i(\mathbf{r},t)$ then delayed neutrons are produced at the rate $\lambda_i M_i(\mathbf{r},t)$ where λ_i is the decay constant of the ith type of excited nucleus. The quantities $M_i(\mathbf{r},t)$ clearly satisfy the following equation:

$$\frac{dM_i(\mathbf{r},t)}{dt} = \beta_i\nu_p N(\mathbf{r},t) - \lambda_i M_i(\mathbf{r},t) \quad (13)$$

The fission rate density satisfies an integral equation of the form:

$$N(\mathbf{r},t) = \nu_p \int\int N(\mathbf{r}',t-T)P(\mathbf{r},\mathbf{r}',T)dTdV' + \Sigma\lambda_i \int\int M(\mathbf{r}',t-T)P(\mathbf{r},\mathbf{r}',T)dV'dT \quad (14)$$

† *Cf.* "The Science and Engineering of Nuclear Power," Vol. II, Chapter 8 (Addison-Wesley Press, Cambridge, 1949).

The integrals are extended in space over the region occupied by fissionable material, and in T from zero to infinity. In order to investigate (14) we first consider the simpler equation

$$N(\mathbf{r},t) = \xi \int N(\mathbf{r}',t-T)P(\mathbf{r},\mathbf{r}',T)dTdV' \quad (15)$$

In our discussion of the properties of (15) we shall regard ξ as a purely mathematical parameter, not necessarily related to the number of neutrons per fission. We may look for solutions of (15) of the form

$$N(\mathbf{r},t) = N_\gamma(\mathbf{r})e^{\gamma t} \quad (16)$$

For each value of ξ there will be an infinite set of γ's for which a solution of the form (16) exists. This set has a maximum γ which is positive for high ξ's and negative for smaller ξ's. The function $N_\gamma(\mathbf{r})$ corresponding to this maximum γ is everywhere positive. The functions corresponding to the algebraically lower values of γ are all oscillatory, N_γ being positive at some points in space and negative elsewhere. For lower and lower γ's the spatial oscillations become more and more pronounced. We will be interested here only in the $N_\gamma(\mathbf{r})$'s corresponding to the highest value of γ for a given ξ. The other functions are related to the behavior of the pile when the fission rates at various positions in the pile are not in phase.* The equation which the functions $N_\gamma(\mathbf{r})$ satisfy is

$$N_\gamma(\mathbf{r}) = \xi \int P_\gamma(\mathbf{r},\mathbf{r}')N_\gamma(\mathbf{r}')dV' \quad (17)$$

where $$P_\gamma(\mathbf{r},\mathbf{r}') = \int_0^\infty P(\mathbf{r},\mathbf{r}',T)e^{-\gamma T}dT \quad (18)$$

For small γ, we have

$$P_\gamma \cong P_0 - \gamma P_1 \quad (19)$$

where $$P_0(\mathbf{r},\mathbf{r}') = \int_0^\infty P(\mathbf{r},\mathbf{r}',T)dT \quad (20)$$

$$P_1(\mathbf{r},\mathbf{r}') = \int_0^\infty TP(\mathbf{r},\mathbf{r}',T)dT$$

* *Cf.* A. M. Weinberg, H. C. Schweinler, *Phys. Rev.* **74**, 851 (1948).

Thus, for small γ, N_γ satisfies

$$N_\gamma = \xi \int N_\gamma P dV' - \xi\gamma \int N_\gamma P_1 dV' \quad (21)$$

For convenience we shall normalize N_γ so that its space integral is unity. Thus,

$$\int N_\gamma dV = 1 \quad (22)$$

For any assembly of fissionable material, there is a value of ξ for which the algebraically largest value of γ is equal to zero. We call this ν_c. A fictitious fissionable material which emitted ν_c neutrons per fission would make the assembly just critical. If ξ is sufficiently close to ν_c the value of the algebraically largest γ is proportional to $\xi - \nu_c$. We shall call the proportionality constant $1/\tau\nu_c$ so that

$$\xi - \nu_c = (\tau\nu_c)\gamma \quad (23)$$

for ξ close to ν_c. As we shall see later, τ is related to the average time it takes a neutron produced in one fission to cause another fission.

We shall now try to make up a solution of the complete problem (13) and (14) out of solutions of Eq. 15 Specifically, we shall write

$$N(\mathbf{r},t) = n(t)N_{\gamma(t)}(\mathbf{r}) \quad (24)$$
$$M_i(\mathbf{r},t) = m_i(t)N_{\gamma(t)}(\mathbf{r})$$

where n, m_i, and γ are functions of time which we shall try to determine to satisfy (15). The statement that γ is a function of time means that $N_{\gamma(t)}(\mathbf{r})$ is the non-oscillating solution of (17) or (21) in which ξ is a function of time. Thus, as time passes, the fission distribution in space may gradually change its shape. In addition to assuming that γ is always close to zero so that Eq. 21 can be used, we shall assume that the time derivative of $M_i(\mathbf{r},t)$ can be obtained by differentiating only the factor $m_i(t)$. This is justified since $N_{\gamma(t)}(\mathbf{r})$ changes only slightly with time. Furthermore, in view of the normalization given by Eq. 22, this approximation produces no error in the time derivative of the total number of excited nuclei in the pile. By virtue of the assumption (24) and the above-mentioned approximation, Eqs. 13 and 14 become

$$\frac{dm_i}{dt} = \beta_i \nu_p n - \lambda_i m_i \quad (25)$$

and

$$n(t)N_{\gamma(t)}(\mathbf{r}) = \nu_p \int n(t-T)N_{\gamma(t-T)}(\mathbf{r}') P(\mathbf{r},\mathbf{r}',T)dTdV' + \Sigma\lambda_i \int m_i(t-T)N_{\gamma(t-T)}(\mathbf{r}') P(\mathbf{r},\mathbf{r}',T)dV'dT \quad (26)$$

In (26) we make a Taylor expansion of n and m_i in the variable T. In the first integral on the right we keep terms up to T in the expansion of n, but in the second integral we keep only the constant term in m_i. This is justified under the assumption that the power level of the assembly does not change appreciably in a prompt generation time, as will be the case so long as the assembly is not too far above prompt critical. The second integral is treated less accurately than the first integral since it is much smaller. (The fraction of delayed neutrons is only about 0.01 so that only about 1% of the fissions will be due to delayed neutrons.) Equation 26 now becomes

$$n(t)N_{\gamma(t)}(\mathbf{r}) = \nu_p n(t) \int N_{\gamma(t)}(\mathbf{r}')P_0(\mathbf{r},\mathbf{r}')dV' - \nu_p \frac{dn}{dt} \int N_{\gamma(t)}(\mathbf{r}')P_1(\mathbf{r},\mathbf{r}')dV' + \sum \lambda_i m_i(t) \int N_\gamma(\mathbf{r}')P_0(\mathbf{r},\mathbf{r}')dV' \quad (27)$$

In expanding $N(\mathbf{r},t-T)$ we have neglected the derivative of $N_{\gamma(t)}(\mathbf{r}')$ with respect to time. Equation 27 will be equivalent to (21) if

$$\xi = \nu_p + \sum \frac{\lambda_i m_i}{n}$$
$$\xi\gamma = \frac{\nu_p}{n}\frac{dn}{dt} \quad (28)$$

Thus, in view of (23), the following relation must hold to make (24) an approximate solution to the problem

$$\nu_p - \nu_c + \sum \frac{\lambda_i m_i}{n} = \frac{\tau \nu_c \nu_p \dfrac{dn}{dt}}{\nu_p n + \Sigma \lambda_i m_i} \qquad (29)$$

In accordance with our assumption that the delayed neutron fraction is small, we may neglect $\Sigma \lambda_i m_i$ compared to $\nu_p n$. Thus, (29) becomes

$$\tau \frac{dn}{dt} = (k_p - 1)n + \frac{1}{\nu_c} \sum \lambda_i m_i \qquad (30)$$

where k_p the prompt multiplication factor is equal to ν_p/ν_c. Equations 25 and 30 are equivalent to (1) with

$$c_i = \frac{1}{\tau \nu_c} m_i; \qquad A(t) = \frac{1}{\tau}(k_p - 1);$$

$$\text{and} \qquad g_i = \frac{\beta_i}{\tau}.$$

(To our approximation the term ν_p/ν_c in the definition of g_i may be considered equal to one.) From Eqs. 25 and 30 it follows that only two quantities characterizing the pile enter into the kinetic relationship, namely the value of ν_c and τ. (This assumes that the delayed neutrons behave in the same way as the prompt neutrons.)

In general, one is interested in treating the case where the properties of the pile are themselves varying with time. If the variation is slow compared to the prompt generation time, Eqs. 25 and 30 still apply, but k_p becomes a function of time. The variation of τ with time can be neglected.

The physical significance of τ can be seen in the following way. We write

$$N_\Gamma = N_0 + \eta_\Gamma$$

where N_0 is the solution of (21) when $\xi = \nu_c$ and where $\gamma = 0$. Since

$$\int N_\Gamma dV = \int N_0 dV = 1, \qquad \text{we have} \qquad \int \eta_\Gamma dV = 0$$

We assume that γ is small so that η_Γ will also be small. Then, (21) becomes, to first order in η,

$$\eta_\Gamma = (\xi - \nu_c)\int P_0 N_0 dV' + \nu_c \int P_0 \eta_\Gamma dV' - \xi\gamma \int N_0 P_1 dV' \qquad (31)$$

If (31) is integrated over the region occupied by fissionable material, we obtain

$$(\xi - \nu_c) = \nu_c \gamma \frac{\int\int P_1 N_0 dV' dV}{\int\int P_0 N_0 dV' dV} - \nu_c \frac{\int\int P_0 \eta_\Gamma dV' dV}{\int\int P_0 N_0 dV' dV}$$

It is reasonable to expect that since $\int \eta_\Gamma dV = 0$, the last term in this equation will be smaller than the others. If this term is neglected, we obtain by comparison with (23),

$$\tau \cong \frac{\int\int P_1 N_0 dV' dV}{\int\int P_0 N_0 dV' dV} \qquad (32)$$

Thus τ is the average time it takes a prompt neutron to produce a fission.*

In actual cases it is not correct to assume that the function $P(\mathbf{r},\mathbf{r}',T)$ applies to delayed as well as prompt neutrons since the spectrum of the latter is, in general, different from that of the former. Hence, one must introduce the functions $Q_i(\mathbf{r},\mathbf{r}',T)$ which give the probability that a delayed neutron of the ith kind which is liberated at $\mathbf{r}'$ produces a fission at $\mathbf{r}$ at a time T later. By a simple extension of the above arguments it can be shown that (30) must be replaced by

$$\tau \frac{dn}{dt} = (k_p - 1)n + \frac{1}{\nu_c} \sum \lambda_i \epsilon_i m_i \qquad (33)$$

where $$\epsilon_i \cong \frac{\int\int Q_i N_0 dV' dV}{\int\int P_0 N_0 dV' dV}$$

Thus ϵ_i is essentially the probability that a delayed neutron of the ith kind will produce a fission divided by the probability that a prompt neutron will produce a fission.

It is interesting to note that if one of the delay periods is very short the m_i corresponding to that period may be eliminated from the equations. If the logarithmic time derivative of m_1, for

* For a bare assembly which can be treated by age diffusion theory this relation is rigorous, since η_Γ is then equal to zero.

example, is small compared to $1/\lambda_1$ then (25) gives the following solution for m_1:

$$m_1 \cong \frac{\beta_1 \nu_p}{\lambda_1} n - \frac{\beta_1 \nu_p}{\lambda_1^2} \frac{dn}{dt} \qquad (34)$$

If this is substituted into (33) we find

$$\left(\tau + \frac{\beta_1}{\lambda_1}\right) \frac{dn}{dt} = [(k_p - 1) + \beta_1]\, n + \frac{1}{\nu_c} \sum \lambda_i \epsilon_i m_i \qquad (35)$$

Hence the short delay period is, in effect, lumped in with the prompt generation time, and the effective prompt multiplication is changed accordingly.

In many cases of practical interest, some fissions are caused by neutrons emitted from a neutron source placed in the assembly. If the number of fissions produced directly by the source neutrons is s, then it can be shown by arguments similar to the above, that (33) is replaced by:

$$\tau \frac{dn}{dt} = (k_p - 1)n + \frac{1}{\nu_c} \sum \lambda_i \epsilon_i m_i(t) + \chi s \qquad (36)$$

If the fissions produced by the source have a spatial distribution proportional to $N_0(\mathbf{r})$, χ will be equal to unity. Otherwise χ will be slightly different from unity (usually a little larger).

When the assembly is undercritical, (25) and (36) have a time independent solution of the form

$$n = \chi s/(1 - k_p - \epsilon_i \beta_i) \qquad (37)$$

Fission rate is thus inversely proportional to the amount by which the assembly multiplication differs from unity.

Comparative Survey of Ion Guns—III

In this last of a series of three papers, the necessary refinements for good ion-gun design and focusing are discussed

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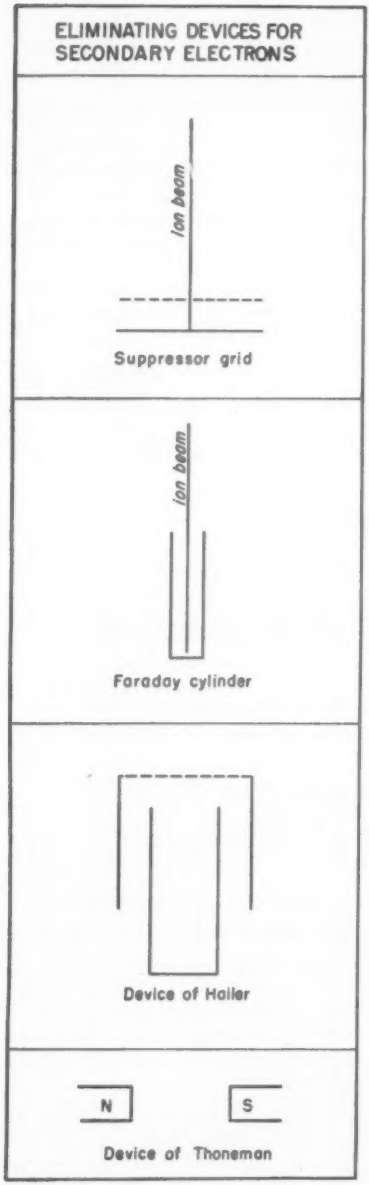
WE NOW SUMMARIZE some questions in close connection with ion sources, such as the elimination of secondary electrons, the regulation of gas flow, the magnetic analysis of the beam, the focusing and the power supply.

Editor's Note: The three papers in this series combine a description and comparison of some kinds of ion guns which have been described in the literature since Thomson's experiments in 1913. In the two papers which preceded this one [NUCLEONICS **4**, No. 5, 7; No. 6, 12 (1949)], representative ion sources and the general properties and specific characteristics of typical guns were discussed.

Eliminating Secondary Electrons

The emission of secondary electrons at the target can falsify measurements about ion sources. According to more recent publications, it seems that most currents measured before 1935 were probably exaggerated in a ratio as high as five to one.

Secondary Electrons—Emission of secondary electrons is the same phenomenon as that experimentally studied by Townsend for electrical discharges



(gamma coefficient or third Townsend's coefficient). According to more recent theories, a positive ion which reaches a wall is generally neutralized by tunnel effect at some distance from it (of the order of 10^{-10} m). The bound energy is generally emitted as a photon, which may strike the wall and push out one or several electrons. If not, the energy may be transferred directly to the wall; electrons are also emitted by such means, where γ is the number of electrons emitted, not including those of neutralization. Numerical values are given in tables (for instance, those of Knoll, Ollendorff and Rompe). Because of the previous mechanism, γ is never zero, even at very low incident ion energies. However, it increases generally with energy.

Also γ depends on the kind of ion and the material of the wall; numerical values are generally between 10^{-2} and 5. The current of electrons emitted is most generally negligible compared to that of incident ions. But those electrons may in turn strike the walls, and pick out tertiaries, etc. Final amplification coefficients may reach rather high values, and the corresponding current is not negligible compared to that of primary ions, but may reach values as high as 500%.

In accelerating devices, this results in some troubles. The power consumption increases considerably. Let us take for instance 10^6 volts and a main current of 100 microamperes. The main power consumption is only 100 watts. But if there are 500% of secondary electrons, the increase in power consumption is proportionally important. These electrons are generally not focused; they strike the walls or the lenses anywhere, producing heating, outgassing, and perhaps, leaks, melting, *etc.* X-rays are emitted. In measurement devices, these effects result in falsification of the target current. Very poor ion sources seem marvelous

when no device is provided to eliminate these secondary electrons.

Eliminating Secondaries—Initially, suppressor grids were used in ion sources as in electronic tubes to eliminate secondary electrons. Because the secondary electrons are generally very slow (a few electron volts), a very low voltage suffices to return them to the target. Sometimes, the target is rendered positive with respect to the last electrode of the source, this one acting as suppressor. Such a method is only possible when the ions leave the source with relatively high speeds, in high voltage sources, for instance. But, in spite of the suppressor, an appreciable fraction fails to be sent back to the target, and these electrons are multiplied (as explained above) into an appreciable quantity.

Tuve, Dahl and Hafstad (*19*) and many others used Faraday cylinders (a few centimeters in diameter and about 10 cm in length) as targets. The secondary electrons are generally intercepted by the side walls of the cylinders. Hailer (*6*) [and see also Craggs (*8*)] states that such a method does not provide complete elimination because some electrons always succeed in leaving the cylinder. But as their motions have a high probability of being almost parallel to the axis, the combination of Faraday cylinder and suppressor grid provides complete elimination. Heiler's method is so far considered as very satisfactory.

Thoneman (*51*) describes a completely different device. He uses a magnetic field of several hundred gauss parallel to the surface of the target. Because secondary electrons are slow, they are immediately sent back.

Regulation of Gas Flow

The problem of regulating the gas flow is an important one; ordinary stopcocks fail completely in maintaining stability of pressure.

The gas is generally provided by a flask or an electrolysis apparatus at atmospheric pressure; the ratio of pressures between those devices and the source is about 100,000 to 1 and depends upon the kind of source.

Palladium tubes are frequently used for hydrogen because they provide purification of the gas by osmosis. We pointed out previously that regulating the temperature provides a regulation of the gas flow.

Many experimenters use needle valves. The needle is moved by means of a bellows. If the cones are suitably adjusted, very stable pressures are available in the sources.

Fowler (*87*) used another device, which is extremely simple and rugged. The central portion of a german-silver cylindrical tube is flattened and bent into a U-shaped spring. A screw allows the opening or closing of the spring, thus regulating the flow. The performance of Fowler's "leak" seems very satisfactory. Baldinger *et al.* (*88*) described a somewhat similar apparatus.

Magnetic Analysis

It is known that when a charged particle (mass m, charge q) of speed v crosses a magnetic field (length L) of induction B perpendicular to v, it undergoes a deflection α given by

$$\tan \alpha = qBL/mv = BL\sqrt{q/2mU}$$

where U is the accelerating potential.

We obtain another formula by taking into account the fact that the charge is an integral multiple of the elementary charge $\epsilon = 1.60 \times 10^{-19}$ C and by expressing the mass m in terms of the mass unit 1.66×10^{-27} kg. Thus

$$\tan \alpha \simeq 9{,}800BL\sqrt{Z/2AU}$$

Z and A having their usual significance in nuclear physics. The sign $\simeq$ means that we neglect the mass defect and use A instead of M.

Fundamental Requirements—In that formula, B must be expressed in Wb/m^2

($= 10^4$ gauss), L in meters, and U in volts. For instance, if $U = 5{,}000$ volts, $B = 0.1$ Wb/m^2, and $L = 0.1$ m, and assuming protons: $\tan \alpha = 0.98$. Assuming deuterons or molecular hydrogen ions: $\tan \alpha = 0.49$. If α is taken to be a constant, B must vary as $(A/Z)^{1/2}$, if U is constant, and as $U^{1/2}$ if A/Z is constant.

Generally, α is given by the apparatus, and B is controlled by varying the electric current in the coils. It may be assumed as a first approximation that they are proportional.

Apparatus—A complete description of a mass monochromator is unnecessary for this discussion. It is used to separate the desired from the undesired ions and generally consists of one or two electrostatic lenses, an electromagnet, and two targets, one of which is along the axis of the lenses, and the second in a direction of angle α of about 20 to 45°. A complete description of such apparatus is given by Jorgen Koch (*25*). Another device in which α can be varied is described by Tuve, Hafstad and Dahl (*16*). Details concerning magnetic analysis are also given by Fowler and Gibson (*15*) and by others.

Von Ardenne (*46*) uses a very different device for separating atomic and molecular deuterium ions before acceleration. The idea is to avoid power consumption for acceleration of undesired ions. At the output of the source is a magnetic lens. It is known that the focal distance for such a lens depends on the mass of particles. At a given distance from the lens is a screen with a small aperture. Desired ions are focused into this aperture; undesired ones are not and consequently most of them are stopped by the screen.

Target current is generally plotted as a function of coil current. If the ions are monokinetic, the curve presents some peaks corresponding to the different values of A/Z. For instance, in a hydrogen ion beam, peaks correspond to H^+, H_2^+, H_3^+ ($A/Z = 1, 2, 3$). But they are seldom alone. Theoretically, the protons give the maximum deflection (presence of positrons or positive mesons being of course excluded). But, frequently, one or two peaks correspond to more easily deflected beams. They are protons arising from molecular ions broken during the acceleration which were affected by only a fraction of the potential difference. Thus, their energies are less than that of protons originated directly in the source. One also observes peaks corresponding to less easily deflected ions than H_2^+; they are parasitic ions such as $O^{++}(A/Z = 8)$, $Hg^{+++++}(A/Z = 40)$ *etc.*, arising from impurities of the gas or from the liquid used in the pumps.

The breadth of the peaks depends only on the perfection of electrostatic focusing and homogeneity of the magnetic field. This is no longer true with heterokinetic ions; breadth of the peaks depends then mostly on the dispersion of speeds and may be used for computing it approximately.

Focusing

The focusing of the ion beam when arising from the source may be studied by general methods of ion optics. We make no attempt here to give a general survey of that science, but only to summarize some interesting results.

Lens Requirements—It is known that, in accelerating tubes, focusing is provided by dividing the high voltage by means of capacitors; each fraction is applied on an electrostatic lens. Experimental results show that almost the whole focusing depends on the first lens near the ion source. If its voltage is not correct, it is generally impossible to obtain a satisfactory spot on the target.

Because all types of ion sources deliver divergent beams of ions, focusing is not easy. Capillary arc sources generally need complicated systems of

lenses; a complete description is given by Tuve, Dahl and Hafstad (*19*); see also (*16*). High voltage sources need higher voltages for focusing, but less complicated lenses. The source is generally fitted in the upper cylinder of the first lens. The same design may be used in oscillating electron sources and perhaps in high-frequency ones. Allison used it with a capillary arc (*29*).

Some experimenters prefer magnetic focusing for the first lens. It is obviously more easy to adjust a current of several amperes than a potential of some 10^4 to 10^5 volts.

In every case, it is necessary to provide bellows for adjusting the position of the source with respect to the lens and of parts of the lens with respect to each other.

Electrostatic Dispersion—The limiting spot size is determined in great measure by the electrostatic dispersion of the beam. Let us consider two identical charged particles traveling together with the same speed. They exert on each other two different forces: (1) an electrostatic repulsion

$$F_R = (1/4\pi\epsilon_0)(q/r)^2$$

and (2) a magnetic attraction, because they correspond to parallel currents

$$F_A = (\mu_0/4\pi)(qv/r)^2.$$

It may be seen that

$$F_A/F_R = v^2\mu_0\epsilon_0 = (v/c)^2.$$

In the case of protons of 10,000 volts, v is only 1.4×10^6 m/s, so that F_A/F_R is about 2.2×10^{-5}, and F_A can be completely neglected. This would not be the case with electrons of the same energy.

The effect of mutual repulsion is not at all negligible. It must be noted that, in a beam of 1 ma of electrons at 10,000 volts, the speed is 6×10^7 meters per sec, and the density of charge is 1.7×10^{-11} coulombs per meter. On the other hand, protons of the same energy have a much lower speed, and the density of charge becomes 7×10^{-10}. The electrostatic dispersion of a proton beam is much higher than that for an electron beam of the same energy and current because the charge per unit length is higher and the attractive force F_A is negligible.

Complete treatment of this problem is given by Fowler and Gibson (*15*). Their results may be summarized as follows. Let us consider an initially parallel beam a cm in radius; its radius becomes $2a$, $3a$, $4a$, at distances given by $0.00188A$, $0.00280A$, $0.00358A$, where

$$A = aU^{3/4}Z^{1/4}/\mathfrak{M}^{1/4}I^{1/2}$$

with U expressed in volts and I in amperes; Z is the number of elementary positive charges and $\mathfrak{M}$ the molecular mass of ions. Fowler and Gibson state that, for instance, for a proton beam of 20,000 volts initially 0.375 cm in radius, the corresponding distances are 16.8 cm, 24.9 cm and 31.9 cm. For further information about focusing, see for instance references *89*, *90*, *91*, *92*.

Power Supply

With this consideration, we conclude our review of ion sources, except to note that details of power supplies are given by most of the authors referred to in the complete bibliography. See also a very complete description by Craggs (*93*).

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Regulation of Gas Flow

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Power Supply

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Report on Los Alamos Information Meeting*

THE INFORMATION MEETING held at Los Alamos Scientific Laboratory May 5–7 is one of several such classified meetings which the Atomic Energy Commission holds each year. The purpose of these meetings is to facilitate the full interchange of ideas among AEC personnel on subjects of common interest, save for certain special topics.

Generally these meetings have been run along the lines of conventional physical society meetings with a large number of short papers and only a very few longer, invited papers. This time a new approach was tried, following more closely the pattern set by recent highly successful conferences. The meeting consisted almost entirely of symposia on broad topics in physics and chemistry. These symposia were so arranged that an introductory speaker discussed the broad outlines of the subject, and was followed in discussion by a selected group of contributors, who were specialists in the field, and by audience participants.

Because the conference dealt with topics rather than with special papers, discussion of some unclassified as well as considerable classified work took place. This arrangement makes possible discussion here of some of the *unclassified* work. In these meetings contributors necessarily discussed not only their own work but also that of their colleagues. Hence, in the following, names and places are sometimes glossed over.

Housing limitations at Los Alamos placed an upper limit of 150 on the number of visitors that could be accommodated. Nevertheless a broad representation was obtained, including scientists engaged in classified work for the AEC from:

Argonne National Laboratory, Brookhaven National Laboratory, California Institute of Technology, Carbide and Carbon Chemical Corp., Columbia University, Duke University, H. K. Ferguson Co., General Electric Co. (Hanford and Schenectady), Kellex Corp., Iowa State University, Massachusetts Institute of Technology, Monsanto Chemical Co., National Bureau of Standards, Naval Radiological Defense Laboratory, North American Aviation, NEPA Oak Ridge, Oak Ridge National Laboratory, Princeton University, Rand Corporation, Sylvania Electric Corp., University of California, University of Chicago, University of Wisconsin, Washington University, and Westinghouse Electric and Manufacturing Co.

The chairmen and principal contributors to the various sessions included:

L. W. Alvarez, E. B. Asheraft, J. A. Ayers, H. H. Barschall, S. Bernstein, G. E. Boyd, N. E. Bradbury, F. G. Brickwedde, B. Brixner, H. Brooks, A. R. Brosi, G. Chew, R. F. Christy, H. Etherington, F. G. Foote, S. Freed, D. K. Froman, J. H. Frye, M. Goldberger, L. Goldstein, A. C. Graves, F. T. Hagemann, E. F. Hammel, B. Hamermesh, W. C. Hazen, D. J. Hughes, F. W. Hurd, J. W. Kennedy, K. A. Kraus, A. S. Langsdorf, Jr., S. Lawroski, E. Long, J. H. Manley, W. H. Manning, C. Mark, M. G. Mayer, W. E. Ogle, H. W. Panofsky, G. W. Parker, M. D. Peterson, L. J. Rainwater, F. Reines, L. D. Roberts, G. T. Seaborg, E. Segrè, R. Serber, A. U. Seybolt, S. Siegel, R. W. Spence, C. Starr, F. L. Steahly, J. A. Swartout, R. F. Taschek, E. Teller, L. Tonks, G. L. Weil, A. M. Weinberg, B. Weinstock, V. Weisskopf, J. A. Wheeler, E. P. Wigner.

Symposia in physics and chemistry included talks on the following topics: nuclear forces, power-breeder reactors, neutron cross-section measurements, ion exchange processes, and cryogeny and nuclear physics. Special meetings on a variety of topics including shielding, fission physics, and effect of radiation on chemicals took place.

At the nuclear forces symposium, the question of nuclear stability was first discussed. M. G. Mayer and L. W. Nordheim discussed their recent theories that the neutrons and protons within the nucleus could be thought of

* This report was supplied at the request of NUCLEONICS by the AEC Public and Technical Information Service at Los Alamos.

as assigned to definite orbits similar to electrons in the atomic theories. The evidence for this spin-orbit coupling and the assignment of such orbital states was explained. It was evident that there was no unique way of assigning these but that the schemes proposed account for a large number of special facts concerned with the systematization of nuclei. This scheme attempts to explain the experimentally observed data which seem to center upon the fact that if there are 20, 50, 82, or 126 neutrons or protons present the resulting nucleus shows exceptional stability. Some experimental evidence for one of these "magic numbers," namely 126, was presented by G. T. Seaborg from conclusions drawn from the energy surface in the heavy region. A systematization of alpha particle decay was presented in this connection by Seaborg.

The nuclear forces session then turned to the examination of high-energy scattering data. The Berkeley group, including Alvarez, Chew, Panofsky, Segré, and Serber, reported on the experiments and analyses of proton-proton and neutron-proton scattering. The most puzzling result seems to be that the proton-proton scattering experiments strongly indicate that there are no repulsive forces in the higher orbital states. Thus the phenomenon of saturation of nuclear forces can no longer be explained by invoking these repulsive forces as has usually been the case. Goldberger and Chew described a scheme of theirs to explain the number of deuterons created when a high energy neutron hits a nucleus. In their picture, the incoming neutron selects a bound proton of appropriate momentum and combines with it to form an emerging deuteron. Their calculations show that this process is entirely feasible. It can perhaps best be described as the inverse of Serber's "stripping" calculation.

Some light element data was discussed and, in particular, Taschek reported the Los Alamos evidence of the probable existence of an excited state of the alpha particle at about 22 Mev, as shown by the production of a 20-Mev gamma ray from the $H^3(p,\gamma)He^4$ reaction. It was emphasized that evidence is not complete since so far only the sharp rise of the cross section with increasing proton energy has been noted, but not a real leveling off or turning point.

The cryogeny session concerned itself with the interconnection of nuclear physics, and in particular neutron physics, with low temperature work. A great deal of discussion took place about the advisability of repeating the experiments on the scattering of neutrons by ortho- and parahydrogen at about 20° K. While the most accurate experiment to date was performed at Los Alamos in 1945, it would be valuable to repeat the parahydrogen scattering part in particular, with greater care. It is hoped that from this, we would obtain what in Schwinger's theory would be called the effective ranges and scattering amplitudes for the neutron-proton forces in the singlet and triplet states. Information about the singlet state may be difficult to obtain because experimental accuracy

EDITOR'S NOTE: The amount of research work going on in the nucleonics field has increased to the point where it is impossible for the individual interested in the activities of the field to keep pace with the month-to-month developments. To give its readers a more complete picture of the field, NUCLEONICS has instituted this feature. In the future, we plan to publish technical progress reports on the work being done at many of the important AEC, university and industrial laboratories.

would have to be pushed towards the limit. A particularly nice example of the connection between neutron and low temperature work was shown by the proposed experiments on the analysis of the ratio of He^3 to He^4 in low temperature samples. Use is made of the fact that the slow neutron cross section for absorption in He^3 is so very large compared to that of He^4. This permits sampling by absorption measurements without destroying experimental conditions. Recent work on the absence of the lambda point in He^3 from the flow properties was presented by Weinstock of the Argonne National Laboratory.

Earl Long of the University of Chicago spoke on the scattering of slow neutrons from He I and He II and the connection with the Bose-Einstein degeneracy. Finally the cryogeny symposium discussed the possibility of obtaining low temperatures by nuclear spin alignment. Attention was drawn to the fact that this idea, proposed in the thirties, was now beginning to come within the immediate realm of possibilities, and proposed experimental details were discussed by L. D. Roberts of the Oak Ridge National Laboratory.

The symposium on nuclear cross-section measurements emphasized largely the methodology rather than any detailed results. A discussion of techniques in the intermediate energy range concerned itself with the merits of such instruments as the crystal spectrometer, the chopper, and the time-of-flight method using modulated neutron sources. Techniques of measuring inelastic scattering cross sections were discussed during the rest of the cross-section session.

Since the major part of the meetings dealt with classified work, the AEC cannot release here information concerning it. However, the major topics of some of the sessions can be mentioned. The symposium on power-breeder reactors concerned itself with the reactor components, with special emphasis on fuel elements, and chemical processes associated with reactor development, such as waste concentration and disposal. Part of the reactor session was devoted to exchange of views on hazards and the means of preventing them.

The symposium on ion exchange processes put special emphasis on elements formed in fission. For example, the study of complex ion formation by ion exchange methods was reported on.

The special meetings on effect of radiation on chemicals and on shielding were in close connection with reactor development proper. The shielding session, for instance, discussed gamma-ray attenuation theories with respect to reactor shields.

The meeting on fission physics emphasized fundamental information recently gained about the fission process at various laboratories of the AEC and its theoretical interpretation.

BOOKS

Reviewed by Norman R. Beers

THE BIG SECRET, by Merle Colby, The Viking Press, Inc., New York, 1949, 375 pages, $3.00.

This novel by Merle Colby will seem bizarre to any scientist who has had no experience with Official Washington. But it is good reading. It is, as well, a source of factual information, treated imaginatively, that will be more useful, to a stranger trying to understand the ways of Washington, than all the handbooks and guides published by the GPO. The author treats rather deli-

cately the question whether the United States will wind up with atomic power as a monopoly of the majority or of a few, especially as it concerns restrictions on the communication of the results of scientific research. The book is recommended with relish.

NUCLEAR FISSION AND ATOMIC ENERGY, edited by William E. Stephens, The Science Press, Lancaster, Pa., 1948, 294 pages, $5.00.

This book was prepared by staff members of the University of Pennsylvania prior to April, 1946. The book is copyright 1946 and 1948 but was published in this form in early 1949 as a result of controversy on whether any of the book's content was restricted data. Much work has been done and many papers declassified by the Atomic Energy Commission between 1946 and June 1949 so that the "Foreword" by G. P. Harnwell, although still of great interest, is not as apropos now as it was when written in 1946. The same comment may be made about some of the "asides" that appear in the text.

The subjects covered are: Discovery of Fission, Production of Fission, Fission Fragments, Fission Products, Secondary Neutrons, Heavy Nuclei, Theory of Fission, Dynamics of Fission, Early Work on Chain Reactions, Slow Neutron Chain Reactions—Piles, Fast Neutron Chain Reaction, Separation of Isotopes, Chemical Separation Methods, Isolation of Plutonium, and Potentialities of Fission Techniques.

MUST WE HIDE? by R. E. Lapp, Addison-Wesley Press, Inc., Cambridge, Mass., 1949, 182 pages, $3.00.

The author conveys the impression that the probable damage to installations and the casualties resulting from future atomic bomb bursts are well known. The solution, according to Dr. Lapp, is not in hiding (which appears impossible in any case) but in early and extensive dispersion of modern cities. The writer has presented the *satellite city*, the *doughnut city*, and the *rod-like city* in illustration of the dispersion recommended. "Must We Hide" presents yet more evidence by picture and word that the results of war are similar, whether the damage is caused by Greek fire, high explosive or "radiation."

Atomic Energy Commission Publications

THE FOLLOWING AEC DOCUMENTS have been added to the list of publications which the AEC has made available for sale to the public through its Document Sales Agency. This tabulation was selected from Document Sales Agency List No. 11 and supplements NUCLEONICS' previous listings of these documents. At the prices indicated, these publications can be obtained by sending a money order or check made payable to the Treasurer of the United States to the **Document Sales Agency, P. O. Box 62, Oak Ridge, Tennessee.**

MDDC or *AECD**		*Price*
Biology and Medicine		
481	Hyperheparinemia—The Cause of the Hemorrhagic Disease Produced by Total-Body Exposure to Ionizing Radiations (*33 pp*)	$.15
991	The Effects of Irradiation on the Blood and Blood Forming Tissues (*31 pp*)	$.15
1005	Metabolism of Fission Products—Radiotellurium (*13 pp*)	.10
1054	Uranium Poisoning (*3 pp*)	.05

* Documents with numbers 1 through 1779 carry the prefix *MDDC* (Manhattan District Declassification Code); for those numbered 1780 and above, the prefix of *AECD* (Atomic Energy Commission Document) applies.

MDDC or AECD		Price
1764	Homotransplantationof Mammalian Adult Kidney (*7 pp*)	$.10
1845	The Quantitative Determination of C^{14} Activity in Biological Systems by Direct Plating (*5 pp*)	05
1960	Ideal Theory of the Mitotic Index and Its Application to Tissue Growth Measurements (*8 pp*)	.10
1966	Transplantation of Bone Marrow into Dogs that have Received Total-Body Single Dose Radiation (*196 pp*)	.60
1967	The Influence of Age on the Uptake of Radioactive Phosphorus by the Skeleton (*19 pp*)	.10
2016	Thrombopenic Purpura—The Failure of Direct Blood Transfusion to Raise the Platelet Level (*5 pp*)	.05
2062	The Viability of Individuals Heterozygous for Recessive Lethals (*5 pp*)	.05
2066	Stripping Film Techniques for Histological Autoradiographs (*9 pp*)	.10
2122	Radium Poisoning. A Survey of the Literature Dealing with the Toxicity and Metabolism of Absorbed Radium (*31 pp*)	.15
2176	The Effect of Rutin Upon the Response of the Rat to Total Body X-Irradiation (*7 pp*)	.10
2249	Studies of the Kinetics of Potassium Exchange Between Cells and Plasma of Canine Blood in Vitro Using K^{42} (*10 pp*)	.10

Instruments

766	Counting Rate Meter Based on a Design by MIT (*9 pp*)	.10
805	Manufacturing Specifications for the Portable G-M Tube Survey Meter (*6 pp*)	.10
833	Specifications for the Type 961A Scaler (*10 pp*)	.10
1176	Testing of a "Dura Seal" Rotary Seal (*10 pp*)	.10
1284	Fast Linear Amplifier Model B-3 (*2 pp*)	.05
1288	2-Fold G-M Coincidence Unit (*2 pp*)	.05
1297	Model 100 Counting-Rate Meter (*7 pp*)	10
1317	Low Absorption Neutron Proportional Counter (*7 pp*)	.10
1789	Operation Manual for Rochester Ion Meter and Accessory Chambers (*17 pp*)	.10
1865	Summary Report on the Development of Electrometer Radiation Instruments (*20 pp*)	.10
1908	Some Applications of Electronics to Precision DC Measments and Control (*6 pp*)	.10

MDDC or AECD		Price
2082	Quartz Spring Joly Balance (*3 pp*)	$.05
2117	High Voltage Pulser for 184-Inch Cyclotron Electric Deflector (*10 pp*)	.10
2168	High Energy Neutron Detector (*4 pp*)	.05
2214	A Simple Recording System for Small Currents (*1 p*)	.05
2355	An Investigation of the Properties of High Valued Resistors and Methods of Reducing Surface Leakage (*10 pp*)	.10

Metallurgy and Ceramics

1126	The Design and Some Construction Details of Two Laboratory Vacuum Furnaces for Casting Metals (*13 pp*)	.10
2210	Mass Deposition of Completely Resolved Samarium Isotopes (*1 p*)	.05
2294	Application of the High Temperature Calorimeter to the Determination of the Heats of Formation of Na-Sn and Li-Sn Alloys (*36 pp*)	.20
2336	Evidence for and Cross Section of 115-Day Selenium-75 (*4 pp*)	.05
2351	A New Measurement of the Packing Fractions of the Nickel Isotopes (*4 pp*)	.50
2524	Extraction of Cerium (IV) Nitrate by Butyl Phosphate (*10 pp*)	.10

Physics

733	The Reaction $_{38}Sr^{86}(n,\gamma)_{38}Sr^{87*}$ Produced by Thermal Neutrons (*2 pp*)	.05
1356	Quantum Corrections to the Thermodynamic Properties of Liquids With Application to Neon (*8 pp*)	.10
1545	Inelastic Scattering of Neutrons (*15 pp*)	.10
1599	Velocity Distribution of Neutrons Emitted from a Slow Neutron Source (*6 pp*)	.10
1720	Pile Neutron Physics (*9 pp*)	.10
1749	Equations of Neher-Harper Circuit (*9 pp*)	.10
1768	Equations for the Pulse from a G-M Counter (*3 pp*)	.05
1850	Preliminary Report on the "Three Quarter Wave" R-F System for Frequency Modulated Cyclotrons (*23 pp*)	.15
1983	The Rate of Rise of Bubbles (*2 pp*)	.05
2044	Theory of Oscillating Absorber in a Chain Reactor (*15 pp*)	.10
2056	The Mathematical Development of the End-Point Method (*45 pp*)	.20

MDDC or AECD		Price
2060	Binding Energies of Alpha Particles in Medium-Heavy Elements (*3 pp*)	$.05
2077	Superlattice Presence in Cu_2Au and FeCo Systems (*3 pp*)	.05
2107	The *K* Spectra of Element 61 (*6 pp*)	.10
2110	A New Technique for the Determination of Heats of Sublimation of Slightly Volatile Substances (*6 pp*)	.10
2119	Polarization of Nuclear Spins (*9 pp*)	.10
2197	Statistical Error in Absorption Experiments (*21 pp*)	$.10
2273	Observations of Naphthalene Scintillations due to Tritium Beta Rays (*3 pp*)	.05
2275	Effect of the Temperature of the Moderator on the Velocity Distribution of Neutrons with Numerical Calculations for H as Moderator (*10 pp*)	.10
2357	Chang and Eng in Use (*11 pp*)	.10
2363	Small-Angle Scattering of Neutrons in Iron (*7 pp*)	$.10
2373	Mass Spectrographic Assignment of Rubidium Isotopes (*3 pp*)	.05
2395	Condensation of Pure He^3 and Its Vapor Pressures Between 1.2° and Its Critical Point (*5 pp*)	.05

Nuclear Science Abstracts

Vol. 2, No. 5.	Nuclear Science Abstracts (AECD 2460–2471) (*36 pp*) (March 15, 1949)	.25
Vol. 2, No. 6.	Nuclear Science Abstracts (AECD 2472–2481) (*42 pp*) (March 30, 1949)	.25
Vol. 2, No. 7.	Nuclear Science Abstracts (AECD 2482–2529) (*68 pp*) (April 15, 1949)	.25
Vol. 2, No. 8.	Nuclear Science Abstracts (AECD 2499, 2530–2556-H) (*73 pp*) (April 30, 1949)	.25

NUCLEONIC EVENTS

AEC APPOINTS CHEMISTRY ADVISORY COMMITTEE

A five-man advisory committee to assist the Atomic Energy Commission in expanding the chemical phase of its research program has been appointed by the AEC, according to an announcement by Kenneth S. Pitzer, research director of the AEC.

The members of the group are: Farrington Daniels, University of Wisconsin; George Kistiakowsky, Harvard; Joseph Mayer, University of Chicago, Don Yost, California Institute of Technology; and Glenn Seaborg, University of California.

The committee will serve as advisors, both in the selection of projects deserving support and in general policies. Dr. Pitzer has expressed the belief that it should be possible to extend the AEC's chemical program considerably within the funds which seem likely to be available.

CHILD LABOR PROHIBITED IN RADIOACTIVITY WORK

Employment of minors between 16 and 18 years of age in workrooms where radioactive isotopes and other radioactive substances, byproducts in the development of atomic energy, are manufactured, used or stored, has been prohibited by Secretary of Labor Maurice J. Tobin.

The Secretary's order, amending the present Hazardous Occupations Order No. 6 under the Federal Wage and Hour Law, which established a similar prohibition with respect to radium or self-luminous compounds, became effective July 9. Since some substances used in modern industry are naturally radioactive to a very slight degree and

have no harmful effects, the Secretary specifically limited the application of the order to those substances which, because of harmful radiation, require precautions in handling. In this connection, the order states that experience has demonstrated that minors between the ages of 16 and 18 years cannot be relied upon to take the necessary precautions.

The Atomic Energy Commission is said to be already enforcing elaborate safety precautions in plants and contracting laboratories under its jurisdiction. The order, therefore, will affect chiefly the laboratories not directly under the supervision of the commission but which are buying isotopes and other radioactive substances from it in increasing quantities.

BRITISH APPOINT RADIATION PROTECTION COMMITTEE

The British government has appointed a committee (the Radioactive Substances Advisory Committee) to advise on protective measures to safeguard working people and the public in general against the danger of exposure to radiation from radioactive substances and certain irradiating apparatus.

The committee consists of: Sir Henry Dale (chairman), J. P. Baxter, W. Binks, Sir Ernest R. Carling, D. G. Catcheside, Lord Cherwell, Sir John Cockcroft, N. Feather, L. H. Gray, Mark Hewitson, J. F. Loutit, W. V. Mayneord, R. McWhirter, E. R. A. Mereweather, Ralston Paterson, H. S. Souttar, Sir George Thomson, and B. W. Windeyer.

IRE-AIEE TO HOLD SECOND INSTRUMENTATION CONFERENCE

The Institute of Radio Engineers and the American Institute of Electrical Engineers will hold a second annual "Conference on Electronic Instrumentation in Nucleonics and Medicine" at the Hotel Commodore in New York on October 31 and November 1-2. It is expected that an exhibit of associated instrumentation will be held simultaneously.

AEC CONFERS ON NEUTRON DETECTION, MEASUREMENT

A conference on the instrumentation for neutron detection and measurement was held recently at the University of California Radiation Laboratory, Berkeley. Sponsored by the Radiation Instruments Branch of the AEC, the meeting brought together 36 representatives of the AEC and allied governmental and military agencies.

One conclusion reached at the conference was that much work still remains to be done on instrumentation for the measurement of fast neutron dosages.

BRITISH PUBLISH PROSPECTOR'S HANDBOOK

To promote exploration throughout the British colonial territories for ores of uranium, the atomic energy division of the Geological Survey of Great Britain has produced a short technical pamphlet entitled, "A Prospector's Handbook to Radioactive Mineral Deposits." It is available at 20 cents a copy.

The pamphlet contains the fundamental scientific information necessary to guide prospectors, geologists and mining engineers in their search for uranium deposits.

NUCLEAR NEWSMAKERS

Allan G. Shenstone has been appointed acting chairman of the department of physics at Princeton University to replace **H. D. Smyth,** who was recently appointed to the AEC.

Lewis L. Strauss, member of the Atomic Energy Commission, was elected president of the corporation of the Institute for Advanced Studies, Princeton, N. J.,

at its annual meeting recently. **Herbert H. Maass** of New York, who had been both president and chairman of the board, was re-elected chairman of the board.

Joseph Volpe, Jr., former legal adviser to Lt. Gen. L. R. Groves in 1945 and more recently associate general counsel of the AEC, has been appointed general counsel of the AEC.

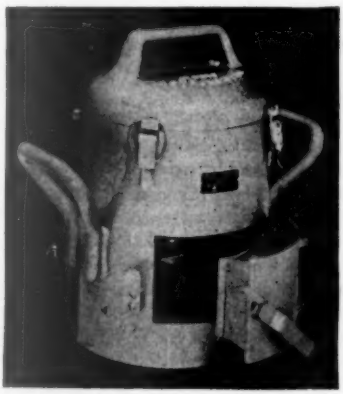
Howard K. Morgan, former assistant director of engineering of the Bendix Aviation Corp. Radio Division, Baltimore, Md., has been appointed director of engineering for the company's new Kansas City division. This division is engaged in special work for the AEC.

Harold C. Miller, former vice president in charge of research and engineering for Charles Hardy, Inc., New York, has been named assistant chairman of the physics department of Armour Research Foundation of Illinois Institute of Technology.

PRODUCTS and MATERIALS

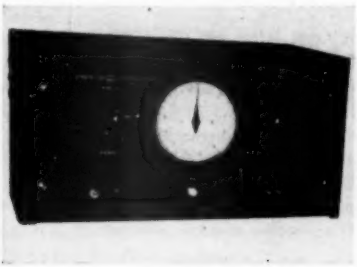
LEAD SHIELD

Atomic Instrument Co., 160 Charles St., Boston, Mass. The model 800 vertical lead shield is steel-cased, aluminum-lined and is designed to offer at least 1½ in. equivalent of lead shielding in all directions. The top is of aluminum and lead construction and, while readily removable, can be securely locked. The dimensions are as follows: inside—5 in. dia × 8½ in. high; outside—9 in. dia × 14½ in. high; door opening—3⅝ in. × 4 in.; weight—250 lbs.



CHRONOSCOPE

American Chronoscope Corp., 316 W. First St., Mount Vernon, N. Y. The model 100 chronoscope is an automatic "stop-watch" which reads time directly



over the range from 10 μsec to 1 sec. It provides an electronic means of discharging a stable capacitor through a stable resistor for the duration of the time interval to be measured. The percentage of charge thus lost is determined by a self-balancing potentiometer. This percentage is indicated by a mechanical pointer on a 5-in. clock face,

which is calibrated directly in units of time.

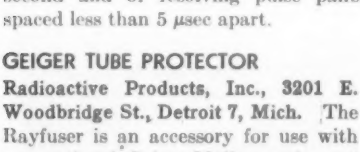
ELECTRONIC COUNTER

Berkeley Scientific Co., Sixth and Nevin Ave., Richmond, Calif. The model 700 electronic decimal counting

unit is designed primarily for counting, timing and frequency measurement work. The four-tube plug-in unit is 5 in. × 5 in. × $1\frac{3}{8}$ in. It contains a scale-of-10 counting circuit which is said to be capable of operating at counting rates in excess of 40,000 pulses per second and of resolving pulse pairs spaced less than 5 μsec apart.

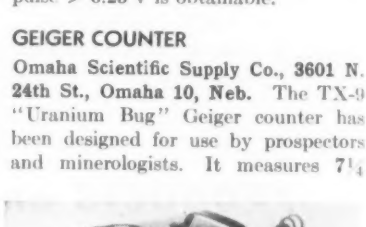
GEIGER TUBE PROTECTOR

Radioactive Products, Inc., 3201 E. Woodbridge St., Detroit 7, Mich. The Rayfuser is an accessory for use with conventional Geiger-Müller equipment to protect the Geiger tube when some disturbance in the circuit causes the applied tube voltage to be excessive. When such a disturbance occurs, a pair of contacts is opened, disconnecting the power to the tube. The Rayfuser is designed to control the power supplied to Geiger tube equipment which: operates on 115 v, 60 cycle a-c; dissipates less than 500 watts; and provides a Geiger tube pulse output such that a negative pulse > 0.10 v or a positive pulse > 0.25 v is obtainable.



GEIGER COUNTER

Omaha Scientific Supply Co., 3601 N. 24th St., Omaha 10, Neb. The TX-9 "Uranium Bug" Geiger counter has been designed for use by prospectors and minerologists. It measures $7\frac{1}{4}$



in. × $4\frac{1}{2}$ in. × 3 in. and weighs $3\frac{1}{2}$ lbs and is self-contained, with batteries, wiring and Geiger tube enclosed. The only part outside of the cabinet is the headphone.

THERMO-PLASTIC

M. W. Kellogg Co., Chemical Mfg. Div., P. O. Box 149, Jersey City 3, N. J. Technical data on Kel-F, a new thermoplastic, is now available. This material reached practical development during the war through research in connection with the design of the uranium diffusion plant at Oak Ridge. Kel-F is a polymer of trifluorochloroethylene. Four fifths of its weight is made up of two halogens, fluorine and chlorine. In its natural state, it is colorless and transparent, although it can be blended with solid fillers and coloring agents. The new plastic is closely related to the

fluorocarbon family of organic compounds, but differs in that some of the fluorine is replaced by chlorine. It is said that the material can be used in the range −320° F to 375° F. Bulletins 1-1-49, physical and mechanical properties; 2-1-49, molding techniques; and 3-1-49, thermal treatment, are available.

PROTECTIVE PAINT

The Australian branch plant of **Lewis Berger & Sons Ltd.,** English paint and pigment firm, plans to produce a paint that will give protection against the gamma rays from radioactive materials. The paint, called Leadoid, was developed in England and is said to be under test by civil defense authorities and by the Royal Navy. It consists of colloidal lead suspended in linseed oil. Leadoid can be applied with a spray gun and, by allowing the linseed oil to oxidize, a solid lead coat can be built up to a thickness of ⅛ in. This lead coat is said to give better protection against gamma irradiation than a solid lead sheet of the same thickness because impurities in rolled lead allow the rays to seep through. The lead coat can be bonded with ease to any surface configuration and to any common metal, to brick and to concrete.

PIPETS, ACCESSORIES

Microchemical Specialties Co., 1834 University Ave., Berkeley 3, Calif. Ultramicro pipets have found wide application in laboratory manipulation of radioactive materials. They may be calibrated either "to contain" or "to deliver" a specified volume. Each pipet is individually calibrated, the calibration being permanently marked on the pipet. Pipets having a volume of 0.5 milliliters or less are marked in lambdas (λ), while volumes over 500 λ's are marked in milliliters. One lambda is equivalent to 0.001 ml. The absolute accuracy of the calibrations depends upon the probable error in reading the miniscus and in the weighings, so it is relatively constant for pipets of various sizes. Therefore, the percentage error in the calibration of a pipet depends upon its volume. By using mercury in calibrating, high accuracy is possible, even for the smaller sizes, because of the favorable weighing factor. Pipets calibrated "to contain" are the most accurate and are recommended for precise volumetric measurements. They must be rinsed out with the solvent after the reagent solution has been delivered. With careful attention it is possible to make measurements reproducible to ±0.1% routinely with "to contain" pipets.

FLUORESCENT ANALYZER

Ultra-Violet Products, Inc., 5205 Santa Monica Blvd., Los Angeles 27, Calif. The Mineralight lamps are devices which can be used to detect and identify such materials as uranium, scheelite, mercury and zircon. They are also said to have application in the food and oil industries and in medicine. Using an electric discharge through mercury vapor enclosed in a fused quartz tube, the Mineralight generates ultraviolet radiation which excites fluorescence in the material under study. The spectral response is used to determine the nature of the test substance.

BUYERS' GUIDE CORRECTIONS

In the Buyers' Guide, which appeared in the "Nuclear Instrument Handbook" in the May issue of NUCLEONICS, the name of the **Nucleonic Corp. of America, 497 Union St., Brooklyn, N. Y.,** was inadvertently omitted from some of the product categories. This company manufactures accessories, counting-rate meters, Geiger tubes, monitors, scalers and survey meters. The **Canadian Marconi Co., Montreal, Quebec,** incorrectly listed as a manufacturer of Geiger tubes, makes accessories, scalers and survey meters.

ABSTRACTS

CHEMICAL PUBLICATIONS

Hood for work with radioactive isotopes, A. K. Solomon, C. A. Foster (Harvard Univ., Boston, Mass.), *Anal. Chem.* **21,** 304–306 (1949). A hood is described in detail that may be used to handle up to 50 mc of radioactive material, although it can be modified for use with more intense sources.

The use of carbon-14 in the determination of the structures of aldoketene dimers, J. D. Roberts, R. Armstrong, R. F. Trimble, Jr., M. Burg (Massachusetts Inst. of Technology, Cambridge), *J. Am. Chem. Soc.* **71,** 843–847 (1949). With C^{14} as a tracer, it was shown that the mixed aldoketene dimer of methyl- and hexylketenes prepared by the Wedekind method does not have a cyclobutanedione-1,3 structure. Molar refractivity, polarization, dipole movement, and ultraviolet absorption measurements indicate that the aldoketene dimers have lactone structures.

Rate of adsorption of barium ions in extreme dilution, by hydrous ferric oxide, M. H. Kurbatov (Ohio State Univ., Columbus), *J. Am. Chem. Soc.* **71,** 858–863 (1949). A study was made of the rate of adsorption of Ba^{133} present in small concentrations (3×10^{-6} and 3×10^{-10} gm atom per liter) by 1×10^{-5} gm mole of hydrous ferric oxide. In spite of the great dilution of the barium, it was not completely adsorbed; instead, an observable adsorption rate was observed, equilibrium being reached in the order of 50 hours. The effect of Ba concentration, *p*H, and ammonium chloride concentration on the adsorption rate was investigated. The data are in accord with an adsorption mechanism involving the displacement of adsorbed monovalent cations by divalent cations. This study was initiated for the purpose of determining optimum conditions for carrier-free target chemistry involving the reactions $Cs(d,n)Ba^{133}$ and $Cs(d,2n)Ba^{134}$.

Fermentation of glucose-1-C^{14}, D. Koshland, Jr., F. H. Westheimer (Univ. of Chicago, Ill.), *J. Am. Chem. Soc.* **71,** 1139 (1949). *d*-Glucose-1-C^{14}, synthesized from *d*(—)-arabinose by the Fischer-Kiliani method, was fermented anaerobically by yeast in phosphate buffers in the absence of combined nitrogen. Almost all the C^{14} was found in the methyl group of the alcohol formed in the fermentation; this is in accord with Embden-Meyerhof fermentation mechanism.

Preparation of high-purity hydrogen deuteride from lithium aluminum hydride, I. Wender, R. Friedel, M. Orchin (U. S. Bureau of Mines, Pittsburgh 13, Pa.), *J. Am. Chem. Soc.* **71,** 1140 (1949). HD, 99% pure, may be prepared easily by adding pure D_2O to a stirred ice-cold slurry of lithium aluminum hydride in *n*-butyl ether. After the vigorous reaction subsides, the evolved gas is collected in an evacuated sample tube.

Scattering of like particles at 100 Mev, F. C. Barker, D. G. Ravenhall (Univ. of Birmingham, Eng.), *Nature* **163,** 20 (1949). Differential and total cross sections were calculated for neutron-neutron and proton-proton scattering on the basis of both exchange and symmetric forces. Comparison of the results of exact calculation with those derived from the use of the Born approximation differ appreciably for symmetric forces; great care should be taken in using the Born approximation at high energies.

Measurements of α-particle energies with the crystal fluorescence counter, I. Broser, H. Kallmann (Kaiser Wilhelm-Inst. for Physical Chemistry and Electrochemistry, Berlin), *Nature* **163,** 20–21 (1949). Studies were made on the suitability of measuring α-particle energies with large single fluorescent crystals of cadmium sulfide. It was found that the intensity of light emitted by a crystal is directly proportional to the energy absorbed in the crystal for α-particle energies from zero to 5 Mev. By using monoenergetic α-particles, the number of pulses was determined as a function of the light flashes; this showed that 80% of all impulses have the same energy. The best crystals needed 7.7 ev to produce one light quanta.

Tensor forces and the neutron-proton interaction, D. G. Padfield (Univ. of Cambridge, Eng.), *Nature* **163,** 22 (1949). Preliminary results are given of calculations (made with the aid of a differential analyzer) on the neutron-proton interaction for values of the range of the central force, r_0, from 1.6×10^{-13} cm to 2.8×10^{-13} cm. For each value of r_0

may be obtained the range of tensor force, depth of square central well, and depth of square tensor well, such that the binding energy, quadrupole moment, and D-state probability for the deuteron are 2.185 Mev, 2.73×10^{-27} cm^2, and 4%, respectively. The results for $r_0 = 2.8 \times 10^{-13}$ cm are compared with the previous accurate calculations of Rarita and Schwinger.

Observations with electron-sensitive plates exposed to cosmic radiation, R. Brown, U. Camerini, P. H. Fowler, H. Muirhead, C. F. Powell (Univ. of Bristol, Eng.), D. M. Ritson (Oxford, Eng.), *Nature* **163,** 47–51 (1949). Electron-sensitive plates were exposed to cosmic radiation and a number of important processes involving charged mesons were observed. Numerous examples of disintegrations produced by π^- and of μ-decay of π^+ particles were observed. A large number of tracks of slow electrons were seen clearly; however, the tracks only rarely originate from the point at the end of the range of π^- particles where the disintegration occurs. Many tracks of grain density corresponding to that of particles near minimum ionization were observed. These tracks furnish useful information on fading, variation of the degree of development with depth, and the sensitivity and other characteristics of the emulsions. Observations of the relation between the rate of loss of energy of a particle and grain density in the track make it possible to estimate the rate of loss of energy for weakly ionizing particles.

Exchange integral with 3*d* wave-functions, E. P. Wohlfarth (Univ. of Leeds, Eng.), *Nature* **163,** 57–58 (1949). Calculations were made of the exchange integral arising in a first-order perturbation calculation of molecular energies according to the Heitler-London method. Wave functions of the 3*d* hydrogenic form having spherical symmetry were used. For a wide range of internuclear distances, the exchange integral is negative, although a positive value was expected on the basis of prior work by Heisenberg, Slater, and others. However, it appears that with a given radial wave function the sign of the exchange integral may be very dependent on the angular wave function. This point is being further investigated. These calculations have bearing on the theory of ferromagnetism.

Microsynthesis of C^{14}-labeled ethylmagnesium iodide, R. Glascock, W. J. Arrol (Univ. of London, England), *Nature* **163,** 61 (1949). Ethyl iodide-C^{14} can be converted on a micromole scale to ethylmagnesium iodide-C^{14} by the reaction with a magnesium mirror in ether solution. The best yield of about 55% was obtained for a reaction period of two hours at 37° C. The product had a high specific activity: about 6 microcuries per micromole.

Use of radioactive phosphorous in plant nutritional studies, R. S. Russell, R. P. Martin (Univ. of Oxford, England), *Nature* **163,** 71–72 (1949). Young barley plants were treated with various doses of P^{32}, and the effects on the root and shoot growth relative to control plants were observed. The results indicate that radiation damage may introduce a much more serious error in tracer experiments than has been realized. Appreciable radiation effects were observed when the P^{32} level was 10 μc per liter. The value of tracer experiments is open to doubt unless the absence of radiation damage is definitely established.

. . . I. W. RUDERMAN

LIFE SCIENCE PUBLICATIONS

Some aspects of the action of sulfonamides—I. Binding of S^{35}-labeled sulfanilamide by escherichia coli, J. Klotz, J. Melchior (Chem. Dept., Northwestern Univ., Evanston, Ill.), *Arch. Biochem.* **21,** 35–39 (1949). Starting with labeled sodium sulfide, S^{35}-labeled sulfanilamide has been prepared in 31% yield. Studies of the binding of sulfanilamide by escherichia coli indicate that less than 0.2% of the sulfanilamide is within the cells and less than 5% is attached to the cell surface.

The transformation in the rat of carboxyl-labeled acetate, methyl-labeled acetate, and labeled bicarbonate into amino acids, D. Greenberg, T. Winnick (Div. of Biochem., Univ. of California Med. School, Berkeley), *Arch. Biochem.* **21,** 166–176 (1949). A comparison was made of the rates of incorporation into protein of various organs and transfer to alanine, aspartic and glutamic acids, and arginine of carboxyl-labeled acetate, methyl-labeled acetate and labeled bicarbonate. The

isotope of the labeled acetates was incorporated to about the same extent. When methyl-labeled acetate was administered, only one third of the C^{14} was found in the COOH-plus amidine groups of the amino acids of liver of intestinal protein. When the other two labeled compounds were fed, almost all of the isotope appeared in these groups. This would indicate that acetate was transferred into α-amino acids without prior oxidation to carbon dioxide. In the main, the experimental data support the theory that acetate enters the tricarboxylic acid cycle via condensation with oxalacetate.

Incorporation of C^{14} of glycine into protein and lipide fractions of homogenates, T. Winnick, E. Peterson, D. Greenberg (Div. of Biochem., Univ. of California Med. School, Berkeley), *Arch. Biochem.* **21,** 235–237 (1949). No isotopic carbon dioxide was evolved when unhydrolyzed protein from $H_2NCH_2C^*OOH$ was treated with ninhydrin. Hydrolysis of protein of carboxyl-labeled glycine experiments to peptides with crystalline pepsin or trypsin, followed by ninhydrin treatment, yielded no isotopic carbon dioxide. These and other data support the view that the C^{14} uptake by protein represents incorporation of amino acids into protein molecules.

Effect of thyroxine and thiouracil on the rate of phospholipid turnover in the liver of the rat, E. Flock, J. Bollman, J. Berkson (Mayo Clinic, Rochester, Minn.), *Am. J. Physiol.* **155,** 402–408 (1948). P^{32}-labeled dibasic sodium phosphate used in studies on adult rats indicated that the specific activity of liver inorganic phosphates appears identical with that of the immediate phosphate precursor of the phospholipids of the liver. Based on this assumption, the rate of phospholipid turnover in the liver and in plasma was increased by thyroxine and decreased by thiouracil.

A radon purification apparatus, H. Dutton (Canterbury Univ. College, Christchurch, New Zealand), *Brit. J. Radiology* **22,** 164–168 (1949). An apparatus is described for the routine purification of radon.

The distribution of radioactivity in tumor-bearing mice after injection of radioactive iodinated trypan blue, C. Stevens, A. Lee, P. Stewart, P. Quinlin, P. Gilson (Dept. of Internal Med., Univ. of Cincinnati, Ohio), *Cancer Research* **9,** 139–143 (1949). Following administration of radioactive dye, tumor tissue showed a much higher concentration of radioactivity than did skeletal muscle or skin, but less than liver, spleen or kidneys. This behavior is similar to that of other radioactive dye preparations.

Distribution of tracer doses of methionine tagged with radiosulfur in normal and neoplastic tissue, A. Kremen, S. Hunter, G. Moore, C. Hitchcock (Dept. of Surgery, Univ. of Minnesota Med. School, Minneapolis), *Cancer Research* **9,** 174–176 (1949). A study of the distribution of tracer doses of D,L-methionine tagged with radioactive sulfur was made in mice with spontaneous and transplanted neoplasms. A high initial concentration of radiomethionine in liver, tumor, kidney and intestinal wall was indicated.

The synthesis of 17-(methyl-C^{14})-testosterone and 21-C^{14}-progesterone, H. Macphillamy, C. Scholz (Ciba Pharmaceutical Products, Inc., Summit, N. J.), *J. Biol. Chem.* **178,** 37–40 (1949). Methyl testosterone and progesterone containing radioactive C^{14} in the side chain have been synthesized in 42% and 26% over-all yields respectively.

The utilization of glycine for the biosynthesis of both types of pyrroles in protoporphyrin, J. Wittenberg, D. Shemin (College of Physicians and Surgeons, Columbia Univ., New York), *J. Biol. Chem.* **178,** 47–51 (1949). N^{15}-labeled glycine was administered to ducks and a human and red cell hemin was isolated. The labeled hemin was degraded and the isotopic concentrations of the nitrogen atoms of the pyrrole structures were studied. The N^{15} concentrations in both types of pyrroles were equal, indicating that glycine is the common precursor in the protoporphyrin molecule.

The synthesis of tricarboxylic acids by carbon dioxide fixation in parsley root preparations, J. Ceithaml, B. Vennesland (Dept. of Biochem., Univ. of Chicago, Ill.), *J. Biol. Chem.* **178,** 133–143 (1949). From parsley root an enzyme preparation has been isolated which has the ability to catalyze tricarboxylic acid formation by the addition of carbon dioxide to α-ketoglutarate. Mn^{++} or Co^{++} or other divalent ion is necessary for the reaction. In the presence of reduced TPN, the product of the initial fixation is reduced to isocitric acid.

Rate of excretion of radioactive sulfur and its concentration in some tissues of the rat after intraperitoneal administration of

labeled **sodium sulfate,** D. Dziewiatkowski (Dept. of Biochem., Johns Hopkins Univ., Baltimore, Md)., *J. Biol. Chem.* **178,** 197–202 (1949). Excretion by rats of S^{35} as sodium sulfate in urine and feces was rapid. By the end of 120 hours, approximately 95% was eliminated by these routes. In this period, the S^{35} concentration in blood, liver and brain fell to relatively low values. At the end of 48 hours, the concentration of S^{35} in liver and blood was the same. Contrasting the rapid fall in blood and liver, the S^{35} concentration in bone increased until the 8th hour and until about the 24th hour in bone marrow. The subsequent fall in S^{35} concentration was slower in bone and bone marrow than in blood, liver and brain.

Preparation of radioactive iodocasein, C. Hamilton, M. Power, A. Albert (Mayo Clinic, Rochester, Minn.), *J. Biol. Chem.* **178,** 213–216 (1949). A procedure is described for preparing radioactive iodocasein of sufficient radioactivity and biologic activity for use in physiological amounts in human metabolic studies.

On the utilization of exogenous sulfate sulfur by the rat in the formation of ethereal sulfates as indicated by the use of sodium sulfate labeled with radioactive sulfur, D. Dziewiatkowski (Dept. of Biochem., Johns Hopkins Univ., Baltimore, Md.), *J. Biol. Chem.* **178,** 389–393 (1949). S^{35}-labeled sodium sulfate administered to rats resulted in the incorporation of some S^{35} into the ethereal sulfate sulfur fraction of the urine. Simultaneous administration of phenol increased the amount incorporated. The close agreement between the specific activities of the inorganic sulfate, total sulfate and ethereal sulfate sulfur fractions suggested that, if sulfur from sources other than pre-existing sulfate is used in the *in vivo* synthesis of ethereal sulfates, that sulfur is first converted to sulfate before becoming conjugated with phenol.

A synthesis of alanine labeled with heavy carbon in the α-position, J. Baddeley, G. Ehrensvärd, H. Nilsson (Wenner-Gren Institute, Univ. of Stockholm, Sweden), *J Biol. Chem.* **178,** 399–402 (1949). A synthesis of D,L-alanine labeled with C^{13} in the α-position is described. Benzaldehyde is reacted with sodium chloroacetate and isotopic sodium cyanide. Decarboxylation and subsequent hydrolysis yields cinnamic acid labeled in the carboxyl group. Reduction to benzalacetone is followed by formation of the oxime which is reduced to the amine and benzoylated. Some 1-phenyl-3-benzamido-1-butene was oxidized to benzoylalanine with $Ba(MnO_4)_2$. The benzoylalanine was hydrolyzed to alanine which was then resolved.

The conversion glycine into serine in the intact rat, W. Sakami (Dept. of Biochem., Western Reserve Univ., Cleveland, O.), *J. Biol. Chem.* **178,** 519–520 (1949). Liver serine was isolated and degraded for isotopic analysis after administration of labeled glycine. Analysis revealed that, under certain conditions, glycine itself is a major source of formate or formate derivative for its conversion to serine.

The utilization of the α-carbon atom of glycine for the formation of acetic and aspartic acids, D. Sprinson (College of Physicians and Surgeons, Columbia Univ., New York), *J. Biol. Chem.* **178,** 529–530 (1949). Data indicate that both carbon atoms of acetic acid are derived from the α-carbon of glycine. The α- and β-carbons of aspartic acid of internal organs protein were also labeled.

Radioiodine in the study and treatment of thyroid disease. A review, M. Kelsey, S. Haines, F. Keating (Mayo Clinic, Rochester, Minn.), *J. Clin. Endocrinol.* **9,** 171–210 (1949). A review citing 153 references.

The behavior of radioiodine in the blood, F. Keating, Jr., J. Wang, T. Luellen, M. Williams, M. Power, W. McConahey (Mayo Clinic, Rochester, Minn.) *J. Clin. Invest.* **28,** 191–198 (1949). After oral ingestion of I^{131} in the form of iodide, levels of total radioiodine in the blood showed significant differences in various thyroid states. Eight hours after ingestion, the mean concentration of radioiodine in serum was 2.06% of the dose per liter in myxedema, 1.28% in euthyroid, and 0.49% in hyperthyroid cases. There are three components of the curve of total radioiodine in serum as plotted against time: an initial rapid increase followed by a brief, rapid fall; an exponential fall; and a third phase which indicates the appearance in the blood of organically bound radioiodine. The rate of disappearance of radioiodine from the blood represents variations in thyroidal function. Observations of urinary excretion of radioiodine may be used to estimate the rate of disappearance of radioiodine from blood. Precipitable radioiodine appeared in the

blood much sooner, rose more rapidly, and reached higher concentrations in hyperthyroid than in euthyroid persons.

Relative measurement *in vivo* of accumulation of radioiodine by the human thyroid gland; comparison with radioactivity in peripheral tissues, T. Luellen, F. Keating, Jr., M. Williams, J. Berkson, M. Power, W. McConahey (Mayo Clinic, Rochester, Minn.), *J. Clin. Invest.* **28,** 207–216 (1949). *In vivo* observations over the thyroid showed substantially more radioiodine was accumulated by the thyroids of hyperthyroid individuals than by the thyroids of euthyroid cases. Euthyroid patients with nodular goiters may at times collect more radioiodine in their thyroids than other euthyroid subjects. Hypothyroid cases show little or no accumulation of iodine in their thyroids. The accumulation curve of radioiodine by the thyroid was similar in form to the curve of urinary excretion of radioiodine, both being exponential in nature. Estimation of the exponential rate constant of the curve of radioiodine accumulation by the thyroid was found to have the same value as the rate constant estimated from observations over the thigh, of urinary excretion, or of analyses of blood for radioiodine. This rate is regarded as representing the rate of disappearance of radioiodine from blood no matter which method is used to obtain it. The rate of disappearance of radioiodine from blood varies according to the state of activity of the thyroid.

The measurement of the iodine-accumulating function of the human thyroid gland, F. Keating, Jr., J. Wang, T. Luellen, M. Williams, M. Power, W. McConahey (Mayo Clinic, Rochester, Minn.) *J. Clin. Invest.* **28,** 217–227 (1949). The iodine-accumulation rate of the thyroid is defined as the proportional rate at which the thyroid accumulates iodine. A basis is given for assuming that the rate applies to all of the iodide ion in the blood and body fluids in equilibrium with the blood. The accumulation rate has been compared with measurements of the quantity of radioiodine excreted in urine, the quantity collected in the thyroid and the disappearance rate of radioiodine from the blood. The accumulation rate may be a less significant measure of accumulating function than thyroid iodide clearance, determined directly from *in vivo* observations over the thyroid obtained simultaneously with determinations of the concentration of radioiodine in plasma.

Studies with colloids containing radioisotopes of yttrium, zirconium, columbium and lanthanum—I. The chemical principles and methods involved in preparation of colloids of yttrium, zirconium, columbium and lanthanum, J. Gofman (Dept. of Physics, Univ. of California, Berkeley), *J. Lab. Clin. Med.* **34,** 297–304 (1949). A study has been made of the preparation of Y, Zr, Cb and La colloids which are suitable for experiment in selective localization of the radioisotopes in bone marrow, liver and spleen.

Studies with colloids containing radioisotopes of yttrium, zirconium, columbium and lanthanum—II. The controlled selective localization of radioisotopes of yttrium, zirconium, columbium in the bone marrow, liver and spleen, E. Dobson, J. Gofman, H. Jones, L. Kelly, L. Walker (Dept. of Physics, Univ. of California, Berkeley), *J. Lab. Clin. Med.* **34,** 305–312 (1949). Zirconium colloids of large particle size disappeared rapidly from the blood stream and deposited mainly in the liver and spleen. Zr and Y colloids of medium particle size disappeared much more slowly from the blood stream and deposited primarily in bone marrow and spleen and secondarily in liver. Once deposited in these organs, no significant change in the distribution pattern was observed for both types of colloids over a period of two to four weeks. Excretion from the body was slow.

An experimental study of the effect of zirconium and sodium citrate treatment on the metabolism of plutonium and radioyttrium, J. Schubert (Argonne Natl. Lab., Chicago, Ill.), *J. Lab. Clin. Med.* **34,** 313–325 (1949). Early administration of zirconium citrate to rats increased plutonium excretion from 1% to 50% and yttrium excretion from 25% to 60% of the injected dose during a 24-hour period. Pu and Y deposits in skeleton were reduced by factors of 6 and 2.6, respectively. Chemical concepts involved in applying metal displacement principles to the removal of radioactive material is discussed.

A study of histochemical iron using tracer methods, K. Endicott, T. Gillman, G. Brecher, A. Ness, F. Clarke, E. Adamik (Natl. Inst. of Health, Bethesda, Md.), *J. Lab. Clin. Med.* **34,** 414–421 (1949). Most of the radioiron of a test meal traversed the duodenal epithelium rapidly. There was no evidence to indicate that the reticuloendothelial system partici-

pated directly in the absorption of iron from the intestine or in the transport of the absorbed iron from the intestine to the liver, blood and other organs and tissues.

Distribution studies in mice following the intravenous injection of diethyl β-iodoethyl amine prepared with radioactive iodine, A. Seligman, A. Rutenburg, O. Friedman (Beth Israel Hospital, Boston, Mass.), *J. Natl. Cancer Inst.* **9,** 261–270 (1949). Diethyl β-radioiodoethyl amine ($I^{131}NM$) was prepared from the chloro derivative by treatment in acetone with sodium iodide. Most of the mustard is rapidly cyclized to the immonium ion with the loss of iodide ion following intravenous injection, but a small portion reaches the tissues intact and penetrates the cells. The highest concentration of radioactivity was noted in blood, lung, and lymph nodes, corresponding to its locus of clinical activity. A lower concentration of activity was noted in kidney, liver and sarcoma 37 of subcutaneous growth.

Determination of carbon^{14} in fatty acids by direct mount technique, C. Entenman, S. Lerner, I. Chaikoff, W. Dauben (Dept. of Chem., Univ. of California, Berkeley) *Proc. Soc. Exptl. Biol. Med.* **20,** 364–368 (1949). It was shown that the C^{14} activity of a fatty acid sample can be readily determined by a direct procedure avoiding dilution of activity and the usual labor associated with the preparation of $BaCO_3$ mount. As many as 50 samples may be mounted in 8 hours with an error in reproduction not in excess of 5%.

Infrared spectrometry in metabolic studies with deuterium-labeled steroids, K. Dobriner, T. Kritchevsky, D. Fukushima, S. Lieberman, T. Gallagher, J. Hardy, R. Jones, G. Cilento (Sloan-Kettering Inst. for Cancer Research, New York), *Science* **109,** 260–261 (1949). An analytical method is presented which permits identification of deuterated organic compounds of biologic interest by means of infrared spectrometry. The sensitivity of the method is very high, and a marked advantage is that the material to be analyzed may be recovered without loss or alteration.

Secretion of radioactive calcium in the hen's egg, C. Comar, J. Driggers, (Florida Agricultural Exp. Station, Gainesville), *Science* **109,** 282 (1949). Of a dose of Ca^{45} administered to a hen, 30% to 35% appeared in the shell of an egg laid 24 hours later. The percentages decreased thereafter. It was calculated that 60% to 75% of the calcium in the egg reached there directly from ingested calcium, with the rest coming from body stores.

. . . BERNARD KANNER

PHYSICAL PUBLICATIONS

Eine tragerlose trennung des radioactiven indiums von cadmium, E. Jacobi (Univ. of Zurich), *Helv. Phys. Acta* **22,** 66–68 (1949). Radioactive indium is produced by a *p-n* reaction on cadmium using 6.5-Mev protons from a cyclotron. The chemical preparation of the resulting activities is described.

Die konversion der gammastrahlen des In^{111}, F. Boehm, O. Huber, P. Preiswerk, R. Steffen (Univ. of Zurich), *Helv. Phys. Acta* **22,** 69–77 (1949). Coincidence measurements were made to determine the *K*- and *L*-internal conversion coefficients of the 173-kev and 247-kev gamma-rays from 2.7-day In^{111} obtained through a Cd(*p,n*) reaction. The geometry of the coincidence measurements is given, and the gamma-ray spectrum as obtained by a spectrometer. The multipole orders of the gamma rays were determined by comparison of the results with the theory of internal conversion.

Laplace transform solution of the two-medium neutron ageing problem, R. Bellma, R. E. Marshak, G. M. Wing (Los Alamos Scientific Lab., N. Mex.), *Phil. Mag.* **40,** 297–308 (1949). The problem solved is that of a point source of monoenergetic fast neutrons above the interface between two semi-infinite media of different slowing-down properties, separated by a plane face.

The energy spectrum of the photon component of cosmic radiation, J. Clay (Univ. of Amsterdam, the Netherlands), *Physica* **14,** 569–574 (1949). The absorption coefficients in lead due to the Compton scattering and pair production by photons are determinable separately. From coincidence-absorption measurements, the exponent in the energy spectrum of the photon component was found to be −1.25 below and −1.07 above the critical energy.

Neutron-proton and neutron-neutron scattering at high energies, F. Rohrlich,

J. Eisenstein (Harvard Univ., Cambridge, Mass.), *Phys. Rev.* **75,** 705–724 (1949). By means of phase shifts and the Born approximation, cross sections are calculated for high-energy *n-p* and *n-n* scattering. Neutral, charged, and symmetrical exchange theories are considered for central and tensor forces of rectangular and Yukawa well shapes. The observed *n-p* cross section at 90 Mev agrees best with that derived from tensor interaction of equal amounts of neutral and charged exchange, but may be consistent with a Yukawa potential of the symmetrical exchange type.

Particle groups from the bombardment of aluminum by deuterons, E. C. Pollard, V. L. Sailor, L. D. Wyly (Yale Univ., New Haven, Conn.), *Phys. Rev.* **75,** 725–731 (1949). The proton and alpha-particle groups emitted at 90° from a deuteron beam bombarding a thin aluminum foil were investigated by means of absorption curves taken with the detector biased so as to count only particles close to the end of the path. Level schemes for Al^{28} and Mg^{25} are given, together with cross sections. The level spacing in the former becomes less at excitation energies of 5 Mev; the structure shows five major groupings. Mg^{25} has a level spacing of about 0.8 Mev.

The emission of radiation in the disintegration of mesons, D. B. Feer (Harvard Univ., Cambridge, Mass)., *Phys. Rev.* **75,** 731–734 (1949). A calculation is made for the probability of disintegration of a meson of integral spin into an electron, a neutrino, and a photon. The energy spectrum of the photons is also given.

On the space distribution of slow neutrons, G. C. Wick (Univ. of California, Berkeley), *Phys. Rev.* **75,** 738–756 (1949). The neutron behavior about a point or plane source of neutrons is discussed for the case of a homogeneous medium.

Energy levels in sulfur nuclei, P. W. Davison (Yale Univ., New Haven, Conn.), *Phys. Rev.* **75,** 757–766 (1949). An absorption method was used to determine the energies of proton groups resulting from the deuteron bombardment of a sulfur target in the form of (gaseous) H_2S in a bombardment chamber. *Q* values are given for thirteen proton groups, corresponding to the ground state and twelve excited states of S^{32}. Proton gamma-ray coincidences to confirm this conclusion have been made. The variation of cross section with angle for the various groups shows a symmetric proton intensity distribution for certain groups and an asymmetric one for others.

On the stability of the isobaric pair In^{115}-$Sn,^{115}$ M. Gurevitch (Univ. of California, Berkeley), *Phys. Rev.* **75,** 767–772 (1949). An investigation was made to determine whether the nuclear spin change involved in the transition Sn^{115} to In^{115} would make this a highly forbidden transition. Spectroscopic analysis indicates a spin of $\frac{1}{2}$ for Sn^{115}. Molecular beam measurement indicates a spin of $\frac{9}{2}$ for In^{115}. Thus, on the basis of a spin change of four, the transition is a "forbidden" one.

On the absorption of slow neutrons by rhodium, R. R. Meijer (Cornell Univ., Ithaca, N. Y.), *Phys. Rev.* **75,** 773–781 (1949). The transmission of neutrons of 0.0044 to 330 ev energy by rhodium was investigated with a time-of-flight neutron spectrometer. A resonance was observed at an energy of 1.21 $\pm$ 0.02 ev, and was fitted with Breit-Wigner parameters. The value of the strength of the resonance was 117 $\pm$ 8 barn-ev.

A cloud-chamber study of the disintegration of lithium by slow neutrons, J. K. Boggild, L. Minnhagen (Inst. for Theoretical Physics, Copenhagen, Denmark), *Phys. Rev.* **75,** 782–785 (1949). The ranges of tritons and alpha particles produced in the reaction $Li^6(n,\alpha)H^3$ were measured in a cloud-chamber. The fact that the corresponding *Q* values disagree suggests the establishment of a new point on the proton energy vs. range curve.

Thresholds for fast neutron fission in thorium and uranium, W. E. Shoupp, J. E. Hill (Westinghouse Research Labs., East Pittsburgh, Pa.), *Phys. Rev.* **75,** 785–789 (1949). With the reaction $Li^7(p,n)$-Be^7 as a neutron source (with maximum neutron energy determined by the energy of the protons from an electrostatic generator), the number of fissions (detected with an ionization chamber) produced in thorium and uranium was found as a function of proton energy.

Bound electron creation in the decay of tritium, P. M. Sherk (Univ. of Illinois, Urbana), *Phys. Rev.* **75,** 789–791 (1949). The probability of an emitted electron entering a bound level following a beta disintegration is considered. For the case of creation of an electron in the *K*-shell, it is shown that the ratio of this process to that of beta emission is 0.0035 for molecular and 0.0065 for atomic

tritium, assuming an endpoint of 16.9 kev. This implies a longer lifetime for the former than for the latter.

The detection of gamma-rays with thallium-activated sodium iodide crystals, R. Hofstadter (Princeton Univ., Princeton, N. J.), *Phys. Rev.* **75,** 796–810 (1949). The crystals were used as detectors in conjunction with photomultipliers. Curves show the pulse width, distribution of pulse sizes, energy discrimination, and dependence on voltage and amplifier bias. Comparisons were made with scintillation counters using other crystals. Experiments which employ photographic plates in conjunction with phosphors are described.

Further experiments on cosmic-ray bursts, H. S. Bridge, B. Rossi (Massachusetts Inst. of Technology, Cambridge), *Phys. Rev.* **75,** 811–818 (1949). The transition curve in lead was investigated by means of coincidence measurements taken on pulses from a Geiger counter tray and an ionization chamber. Altitudes of from a few hundred feet to 30 thousand feet were employed. The results indicate that coincidences observed when the two detectors are separated by lead are due to showers produced by photons or electrons either incident on the lead or produced in it by nuclear interactions.

The radiations from 2.7-day Au^{198}, P. W. Levy, E. Greuling (Oak Ridge Natl. Lab., Tenn.), *Phys. Rev.* **75,** 819–826 (1949). Two beta spectrometers of the semicircular focusing type, one having coincidence detection and the other photographic recording, were used to determine the spectrum of Au^{198}. It was found to consist of an allowed group of electrons of maximum energy 0.966 Mev, plus one strongly and two weakly converted gamma rays. A scheme of decay consistent with the half-life and spectrum involved a group of electrons of maximum energy 0.601 Mev emitted in about 15% of the disintegrations.

The energy spectrum of the delayed neutrons from O^{17}, E. Hayward (Univ. of California, Berkeley), *Phys. Rev.* **75,** 917–919 (1949). O^{17}, produced by the beta decay of N^{17}, is an emitter of delayed neutrons whose energy distribution has been measured by noting the proton recoils obtained in a hydrogen-filled cloud chamber placed near the target in which the O^{17} is formed. The results indicate that the beta decay leaves the O^{17} either in a single excited state of width at least 0.6 Mev, or in more than one excited state. The neutron energy distribution maximum is about 1.1 Mev.

Upper limits of the fission cross sections of bismuth, lead, mercury, gold, iridium, and tungsten for 14 Mev neutrons, A. N. Phillips, L. Rosen, R. F. Taschek (Los Alamos Scientific Lab., N. Mex.), *Phys. Rev.* **75,** 919–922 (1949). The neutrons were produced by a Van de Graaff generator using the $T(d,n)He^4$ reaction. By determining the ratio of the number of fission tracks recorded in a photographic emulsion which had been in contact with a thin foil of the investigated element to the number of such tracks in a similar emulsion in contact with a foil of U^{238}, after each had been simultaneously exposed to about the same neutron flux, the fission cross sections of these elements were found. Each was less than 10^{-5} that of U^{238}.

The intensity of heavily ionizing penetrating particles at 4300 meter altitude, F. L. Hereford (Bartol Research Foundation of the Franklin Inst., Swarthmore, Pa.), *Phys. Rev.* **75,** 923–928 (1949). The ionizing cosmic radiation penetrating various thicknesses of lead was registered by a low-pressure G-M counter. The meson intensity was subtracted, having been obtained from other data. Electrons were excluded as ionizing agents for thicknesses over 100 cm, and the remaining radiation, about 17% of the radiation penetrating 167 cm of Pb was attributed to heavily ionizing particles (probably protons).

Total neutron cross sections of compounds with different crystalline structures, L. Winsberg, D. Meneghetti, S. S. Sidhu (Argonne Natl. Lab., Chicago, Ill.), *Phys. Rev.* **75,** 975–979 (1949). Total neutron cross sections of polycrystalline compounds of hexagonal close-pack, face- and body-centered cubic types were measured with a neutron velocity selector. Scattering amplitudes were determined from the size of the cross-section peaks due to coherent neutron scattering.

The present status of the evidence for the atom-annihilation hypothesis, R. A. Millikan (California Inst. of Technology, Pasadena), *Revs. Mod. Phys.* **21,** 1–13 (1949). The evidence for the theory that cosmic rays originate in intergalactic space through the annihilation of atoms is presented. Curves showing the ionization (counts per minute) produced at various heights and at various magnetic

latitudes are given and interpreted on the basis of the energies and critical magnetic latitudes of entry for cosmic-annihilation rays from He, C, N, and O.

Extensive and penetrating atmospheric showers, R. Maze, A. Fréon, J. Daudin, P. Auger (École Normale Supérieure, Paris, France), *Revs. Mod. Phys.* **21,** 14–20 (1949). Absorption measurements were made on these showers which simultaneously determined their extent. Measured also was the shower-producing properties of particles which passed through a variable thickness of lead. Two groups of particles were distinguishable in the showers, one local and one extensive. Coefficients of absorption were determined for their penetration through lead, as were distributions of the horizontal spread.

The penetrating particles in cosmic-ray showers, G. D. Rochester (Univ. of Manchester, England), *Revs. Mod. Phys.* **21,** 20–26 (1949). The nature of the heavily ionizing particles occurring in showers and the lightly ionizing particles in penetrating showers was investigated with a cloud chamber, coincidence counting trays, and lead absorbers. Particle momenta were measured magnetically. An appreciable fraction of the penetrating particles had properties different from μ-mesons. The penetrating particles may have been protons or π-mesons (or heavier ones). Some of the showers were extremely complex, some consisting mainly of electrons.

Results and problems concerning the extensive air showers, G. Cocconi (Cornell Univ., Ithaca, N. Y.), *Revs. Mod. Phys.* **21,** 26–30 (1949). Coincidence measurements on the extensive air showers revealed a soft component, a penetrating component, and a neutronic component. For the first, the altitude dependence, density spectrum, and spatial spread of the showers are discussed. The relative intensity of soft and penetrating components and their correlation, the penetrating power of the hard component, and its origin, were investigated. Evidence was found that the neutrons are produced by the penetrating component.

The mass of the mesotron, R. B. Brode (Univ. of California, Berkeley), *Revs. Mod. Phys.* **21,** 37–41 (1949). Measurement of the meson mass can be made from combination of measurements of momentum (from curvature in a magnetic field), specific ionization produced, and range in various materials. A meson mass of 215 ± 2 electron masses is thus obtained. Computing the mass of the π-meson on the assumption that it disintegrates into a neutrino and μ-meson, and using 4 Mev as the kinetic energy of the latter, gives the π-meson a mass of 283 ± 7 electron masses.

Photographic evidence for the existence of a very heavy meson, L. Leprince-Ringuet (Ecole Polytechnique, Paris, France), *Revs. Mod. Phys.* **21,** 42–43 (1949). Previous cloud chamber and photographic evidence for the existence of a meson of mass about half the proton mass is summarized, and an additional photograph is shown which contains a star produced by a particle of mass greater than 700 electron masses. This appears to be a negative meson having strong nuclear interaction.

On the mechanism of sudden increases of cosmic radiation associated with solar flares, S. E. Forbush, P. S. Gill, M. S. Vallarta (Carnegie Inst. of Washington, D.C.), *Revs. Mod. Phys.* **21,** 44–48 (1949). It was shown that protons and electrons could be accelerated to 10 Bev by solar phenomena connected with flares. The mechanism by which such particles leave the sun (a "tunnel" is not always present) and the way in which they reach the earth, with the corresponding transit time, are given.

A critique of ionization measurements of nuclear disruptions produced by cosmic radiation, S. A. Korff (New York Univ., N. Y.), *Revs. Mod. Phys.* **21,** 75–81 (1949). Proportional counters used to measure nuclear disintegrations produced by cosmic rays may count slow neutrons by capture, fast neutrons by recoil, and charged emitted particles. Various highly ionizing processes will give counter backgrounds. The method for separating and analysing the counting rates produced by each of these events is discussed; it involves varying the shielding, counter size, pressure and nature of filling gas, *etc.*

Counter pulse shape, C. D. Thomas (West Virginia Univ., Morgantown), *Rev. Sci. Instr.* **20,** 147–149 (1949). The dependence of the pulse height and form for a self-quenching counter on the circuit parameters (resistance and capacitance) is derived theoretically. Comparison is

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made with the data obtained from photographed pulses for a wide range of the parameters.

Conditions for optimum luminosity and energy resolution in an axial β-ray spectrometer with homogeneous magnetic field, J. W. DuMond (California Inst. of Technology, Pasadena), *Rev. Sci. Instr.* **20,** 160–169 (1949). Relations are derived for the electron paths in a spectrometer with uniform axial magnetic field. A ring focus arrangement is used. The line broadening resulting from (1) spherical aberration (from a finite angular aperture); (2) finite width of the selected energy band (determined by the width of the resolving slit at the ring focus), and (3) the effect of an extended source, is discussed. A criterion is given for an optimum condition. Formulas are derived for optimum dimensions, resolution, and intensity of detected beam (luminosity).

The scintillation counter as a proportional device, R. C. Hoyt (Univ. of Rochester, N. Y.), *Rev. Sci. Instr.* **20,** 178–180 (1949). The fluctuations in the gain of a photomultiplier tube were investigated and found to be about 40% (standard deviation). Photomultiplier pulse heights from Po alphas on a ZnS screen had a standard deviation of 27% to 80%, but the contribution from fluctuations in gain was found to be small in this case. Under certain circumstances, two particles losing different amounts of energy in the phosphor can be distinguished if both distribution curves have been obtained.

A pulse amplitude analyzer for nuclear research using pretreated pulses, C. H. Westcott, G. C. Hanna (Natl. Research Council, Chalk River, Ont., Canada), *Rev. Sci. Instr.* **20,** 181–188 (1949). An instrument which classifies pulse heights into thirty channels is described. With ionization chamber and linear amplifier, it gives the frequency of occurrence of ionization pulses of various amplitudes. The instrument was designed for high counting rates and pulses of widely varied shapes and widths.

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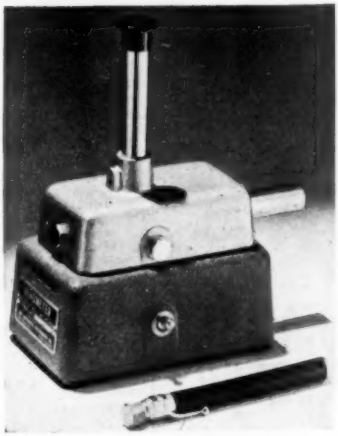

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